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ICHNOLOGY OF THE YEOMAN FORMATION, SOUTHEASTERN SASKATCHEWAN

by

Rozalia Pak ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of **Master of Science**.

Department of Earth and Atmospheric Sciences

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ABSTRACT

The Upper Ordovician Yeoman Formation of Southern Saskatchewan is characterized by distinctive dolomite mottling, which is closely related to biogenic sedimentary structures. Two theories have been proposed for the origin of these mottles: either they represent *Thalassinoides*-like networks or diagenetic haloes, which precipitated around smaller causative burrows. These dolomite mottles are the focus of this study. First, their origin is examined. The types of recognizable biogenic sedimentary structures are described and classified. In doing so, the close relationship between the trace fossils and organic matter of the Yeoman Formation was found to have implications on the accumulation of organic-rich beds called kukersites. Second, since trace fossils may be useful in examining palaeoenvironmental changes, their potential as such in the Yeoman Formation was explored. Finally, diagenetic fabrics associated with the burrows were examined in order to determine if there is a relationship between the trace fossil type and diagenetic fabric.

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SYMBOLS AND ABBREVIATIONS I.

Sedimentary Structures

Laminated

Bedded

Convolute lamination

Dewatering Structures

Soft sediment deformation

Grainstone beds

Fossils and Allochems

Brachiopod

Bryozoan

Cephalopod

Crinoid

Gastropod

Ostracod

Peloid/Pellet

Rugose Coral

Skeletal Fragment

Tabulate Coral

Trilobite

Biogenic Sedimentary Structures

Asterosoma (As)

Chondrites (Ch)

Palaeophycus (Pa)

Planolites (Pl)

Planolites (Pl) filled with organics

Rhizocorallium (Rh)

Skolithos (Sk)

Thalassinoides (Th)

Trychophycus (Tr)

Trypanites (Try)

Indeterminable burrow

Reburrowed organics filled burrow

Reburrowed organics filled boring

Burrow Density

Rare

Present

Common

Abundant

Fully biotubated

Organics

Kukersite K

Organic-rich bed with solution seams

Organic laminae with solution seams

Contacts

Facies contact

Gradational

Sharp

Uncertain

Bored hardground

Bored hardground below K

Burrowed firmground

Burrowed firmground below K

Undulatory

Stylolitic

Solution Seam

Matrix Lithology

Anhydrite

Dolomite

Calcareous Dolomite

Dolomitic Limestone

Limestone

SYMBOLS AND ABBREVIATIONS II.

Diagenesis

Fracture	
Cemented fracture	
Anastomosing low amplitude stylolites	
Wispy solution seams	
Low amplitude stylolite	
High amplitude stylolite	
Solution seams	
Stylo - bedded	
Stylo - mottled	
Horizontal mottles	
Anhydrite nodule	
Chert	
Sucrosic dolomite	
Hopper shaped crystal mold, dolomite cement	
Hopper shaped crystal mold, anhydrite cement	
Diagenetic nodule	
Saddle dolomite cement	SD
Anhydrite cement	A
Calcite cement	C

Well Symbols

Producing oil with Yeoman core	
Water injection well with Yeoman core	
Abandoned with Yeoman core	
Suspended with Yeoman core	
Suspended with Yeoman core	
Producing oil without Yeoman core	
Water injection well without Yeoman core	
Abandoned without Yeoman core	
Suspended without Yeoman core	
Suspended without Yeoman core	

Miscellaneous

Photo	
Sample	

CHAPTER 1. YEOMAN FORMATION OF SOUTHEASTERN SASKATCHEWAN

1.1 INTRODUCTION

The Upper Ordovician Yeoman Formation of Southern Saskatchewan is characterized by distinctive dolomite mottling, which is closely related to biogenic sedimentary structures. Two theories have been proposed for the origin of these mottles: either they represent *Thalassinoides*-like networks or sediment dolomitization in and around smaller causative burrows. These dolomite mottles are the focus of this study. First, their origin was examined. The types of recognizable biogenic sedimentary structures were described and classified. In doing so, a close relationship was observed between the trace fossils and the distribution of organic matter in the Yeoman Formation. Since dispersed organic matter at the seafloor and in the water column provide a key food source for many benthic fauna, their distribution within the burrows is believed to have implications on the nature of *Gloeocapsomorpha prisca*, an enigmatic algal microfossil, which dominates organic-rich accumulations in the Yeoman Formation. The second part of this study investigates the accumulation of deposits dominated by *G. prisca* alginite. The third objective of this thesis to examine the potential of trace fossils as indicators of paleoenvironmental change during the deposition of the Yeoman Formation. Finally, dolomitization and diagenetic fabrics associated with the biogenic sedimentary structures are examined in order to determine if there is a relationship between the type of trace fossil and diagenetic fabric. This first chapter outlines previously documented studies concerning the Yeoman Formation and the equivalent Burrowed 'C' Member of the Red River Formation.

1.2 METHODS

Cores, thin sections and UV light were utilized in the stratigraphic, sedimentologic and diagenetic analysis of the Yeoman Formation. A total of 23 wells (Table 1.1) were examined from the Midale (Township 6-7, Range 11W2); Tyvan (Township 13, Range 13W2); and Ceylon (Township 5-6, Range 19-20W2) pools (Figure 1.1). Core was logged by identifying the biota, ichnology and textural relationships in the rocks. Textures were described using Dunham's (1962) classification scheme as modified by Embry and Klovan (1971). Fifteen of the wells were sampled for thin section, burrow fabric and associated organic analysis (Appendix 1). One hundered and fifteen thin sections were injected with blue epoxy for porosity determination and stained with Alazarin-Red S (Dickson, 1965) to differentiate calcite from dolomite. Samples selected from different trace fossil associations were then prepared for examination of organic microfacies using reflected light microscopy. These samples consisted of blocks ~2 cm x 2 cm that were set in an epoxy resin and then polished using finer and finer grit sizes and finally a

slurry of 0.05 μm alumina suspended in water. A Zeiss Axioplan II microscope equipped with a 100 W UV light source was used for maceral analysis. Samples were observed under water immersion objectives (40 X Apochromat, NA = 1.2; magnification range 400x to 1000x) using 365 nm excitation and 420 nm barrier-emission filter to optimize imaging of kukersite microscopic constituents. Digital images were captured using a Zeiss Axiocam system and Zeiss Vision software. The alginite and other maceral comprising the kerogen/dispersed organic matter assemblages in the kukersite samples have been classified following a scheme shown in Table 3.1.

Table 1.1 List of Examined Cores.

Well Name	Location	Logged Interval	
PCP Weyburn	21/B6-20-06-13W2	2620.0	2648.0 m.
Berkley et al Hume N	41/07-02-09-13W2	2441.0	2447.7 m.
Shell Yeoman	01/06-32-08-16W2	2451.8	2494.0 m.
Berkley et al Midale	21/07-02-07-11W2	2578.0	2597.0 m.
Berkley et al Midale	01/08-03-07-11W2	2579.0	2604.7 m.
Berkley et al Midale	11/07-03-07-11W2	2562.5	2617.2 m.
Berkley et al Midale	21/16-03-07-11W2	2570.0	2591.4 m.
Berkley et al Midale	01/12-02-07-11W2	2543.0	2603.6 m.
Berkley et al Midale	31/11-35-06-11W2/A	2582.0	2610.5 m.
Berkley et al Midale	31/11-34-06-11W2	2568.0	2604.0 m.
Berkley et al Midale	41/02-10-07-11W2	2560.8	2599.0 m.
Rigel Upton Midale	11/9A-28-06-11W2	2590.6	2621.0 m.
Tri Link Tyvan	41/07-17-13-13W2	2152.0	2170.0 m.
Tri Link Tyvan	21/08-17-13-13W2	2143.0	2179.0 m.
Tri Link Tyvan	11/10-17-13-13W2	2152.0	2173.8 m.
Tri Link Tyvan	01/10-28-13-13W2	2160.0	2178.0 m.
Tri Link Tyvan	11/02-29-13-13W2	2147.0	2169.0 m.
Northrock Rich Ceylon	42/11-12-06-20W2	2682.0	2694.1 m.
Husky Ceylon	11/05-08-06-19W2	2704.0	2740.0 m.
Husky Ceylon	41/06-05-06-19W2	2714.9	2749.5 m.
Saskoil Ceylon	01/10-18-05-19W2	2758.5	2774.0 m.
Husky Ceylon	41/10-18-05-20W2	2771.0	2789.0 m.

1.3 Previous Studies

Nomenclature and Stratigraphy

The Upper Ordovician Yeoman Formation of the Williston Basin, the focus of this study, is the lowermost unit of the Bighorn Group, (Figure 1.2). These sediments are Cincinnatian in age (Osadetz and Haidl, 1989). Yeoman deposition commenced approximately 450 million years ago and lasted for approximately 5 million years (Haidl et al., 1997). The Upper Ordovician transgression, which deposited the sediments of the Yeoman Formation, represents the onset of Tippecanoe deposition, during which the Williston Basin straddled the equator (Figure 1.3) and warm, slightly restricted conditions dominated (Sloss, 1963).

The subdivisions of the Bighorn Group of the Williston Basin, differ depending on the author and region of study. There is a marked difference between Canadian and American Terminology (Figure 1.2). Most American studies, situated in Montana, North Dakota and South Dakota, subdivide the Bighorn Group into the Red River, Stony Mountain, and Stonewall Formations (Figure 1.2). The term Red River Formation was first applied by Foerste in 1929 (Kendall, 1976) to the carbonate strata which conformably to disconformably overlie the clastic Middle Ordovician Winnipeg Group (Kendall, 1976). In Canada, Kent (1960) subdivided the Red River Formation into the Yeoman and Herald Members, with the Yeoman defined as the lowermost burrow-mottled carbonate of the 'C' cycle. They were raised to formal rank by Kendall (1976). The Red River Formation is comprised of three carbonate-evaporite cycles: 'C', 'B' and 'A' in ascending depositional order (Porter and Fuller, 1958, 1959; Kohm and Louden, 1978). Although these three cycles are not complete (they have been erosionally truncated, not deposited or their stratigraphic continuity is under debate) throughout the Williston Basin, they are each generally comprised of: 1) thin argillaceous dolomite or dolomitic mudstone, 2) burrow-mottled dolostone or limestone, 3) laminated dolomite and finally 4) nodular anhydrite.

Lower Boundary

Generally, the Yeoman Formation rests disconformably on clastics of the Ordovician Winnipeg Formation or the Cambrian-Ordovician Deadwood Formation (Kendall, 1976; Kent and Haidl, 1999). The base of the Yeoman Formation in southern Saskatchewan denotes the onset of and change to carbonate sedimentation in the Williston basin, on top of Winnipeg clastics. At the peripheries of the basin, where the Yeoman oversteps the depositional limits of the Winnipeg shales, the Yeoman Formation onlaps onto the Cambrian-Ordovician Deadwood Formation (Figure 1.4). The base of the Yeoman can be a sharp erosional surface, with locally reworked Winnipeg clastics found in the overlying Yeoman carbonates. The conformability of this boundary is variable throughout the Williston Basin. Longman et al. (1983, 1987) found that the shales of the underlying Winnipeg Formation graded conformably into the Red River (Yeoman) Formation .

Kendall's Subdivisions of the Yeoman Formation

Kendall (1976) subdivided the Red River 'C' interval (Yeoman Formation and basal Herald Formation) into four informal units (A, B, C and D) in southeast Saskatchewan (Figure 1.5). These units do not show lateral continuity and therefore they cannot be proposed as members. The basal 'A' unit consists of an argillaceous section, which is generally composed of dolomitized limestones or calcareous dolomites. Unit 'B' is the thickest unit comprising one half to one third of the Yeoman Formation. These sediments are predominantly fossiliferous mudstones, with wackstones in some areas. Both the 'A' and 'B' units are characterized by low porosity. The 'C' unit is characterized by the typical Red River mottled wackstones to mudstones and their dolomitized equivalents. Most of the kerogenite layers occur within

this 'C' unit. The uppermost 'D' unit decreases in thickness to the northeast and west and is believed to represent a transitional unit between the Yeoman and Herald Formations. The 'D' unit contains irregular dolomite mottling, some laminated thin bedded bioclastic-lithoclastic grainstones to packstones and rare pisoliths (Kendall, 1976). Overall, Kendall's lithologic description of the Yeoman Formation is similar to that of other authors (Carroll, 1978, 1979; Longman et al., 1987); however, he points out that due to dolomitization and pressure solution the lithologic fabrics in the Yeoman (Red River) Formation are highly variable (Kendall, 1985).

Upper Boundary

The top of the Yeoman Formation depends on whether one includes the transitional unit 'D' of Kendall (1976). Kent and Kissling (1998), believing that this unit represents a shallowing above the below fair-weather wave base conditions that prevailed during Yeoman deposition, named it the Basal Lake Alma Member of the Herald Formation. Since it does not contain the distinctive burrow-mottling, their convention will be adapted in this study. The upper contact of the Yeoman Formation is conformable with the overlying sediments. In core, the transition from the Yeoman to the Herald Formation is gradational with only slight evidence for any break (Kendall, 1976); commonly, it is more easily located on gamma ray logs than in core. Whether the marked change in the gamma ray log is due to the increase in argillaceous material remains to be established (Kent and Haidl, 1999). The conformity of the upper boundary is ubiquitously present throughout the Williston Basin. Longman et al. (1983, 1987) found that the top of the Yeoman Red River 'C' interval has a gradational top, which is demonstrated by the interbedding of the Red River 'C' burrowed and laminated members in Montana.

Kendall (1976) named the remainder of the Red River Formation (cycle 'C' Laminated and Anhydrite members, cycle 'B and cycle 'A'), the Herald Formation. He divided the Herald Formation into three members, with approximately the same division boundaries as the lithologic changes in the Red River Formation. These three members in ascending order are the Lake Alma Member, the Coronach Member and the Redvers Unit. The Lake Alma Member is equivalent to the Red River 'C' Laminated Member, with the Alma Lake Anhydrite corresponding to the Red River 'C' Anhydrite. The correlations of the remaining sections have not been discussed, but the 'B' and 'A' carbonate-evaporite cycles are also found in Saskatchewan. The Red River Formation is overlain by a clastic succession, the Stony Mountain Formation. Tippecanoe sedimentation continued into the Middle Devonian.

Outcrop equivalents of the Bighorn Group in Manitoba and Central Saskatchewan are known as the Tyndall Limestone. The Tyndall Limestone has been subdivided into three members: the Selkirk, Cat Head and Dog Head (Andrichuk, 1959). Kendall (1976) suggested the Yeoman Formation may be equivalent of to these members, however, correlation of outcrop members with subsurface members has not been confirmed.

Regional Extent, Structure and Paleogeography

During the Early Ordovician, the North American craton was emergent. The Tippecanoe transgression during the Middle to Upper Ordovician inundated the major portion of the continent. The Bighorn Group extends throughout and beyond the boundaries of the Williston Basin. It is believed that the Bighorn Group is the preserved remnant of an extensive Upper Ordovician carbonate package whose sediments are thought to have covered the entire craton (Macauley, 1964; Zenger and Lemone, 1995). Burrow-mottled carbonates, with similar characteristics to the Yeoman Formation, can be found from the Yukon to West Texas (Zenger, 1992). The Williston Basin sediments were preserved since it subsided at a different rate than the rest of the Paleozoic margins of the North American craton. On all peripheries of the Williston Basin, the Yeoman (Red River) Formation is truncated by erosional unconformities. Outcrops are found on the northeast margins in both Saskatchewan and Manitoba (Figure 1.6). On the eastern boundary, the sediments end against paleohighs of the Trans-Hudson Orogen, which represents the boundary between the Superior and Churchill provinces of the Canadian craton. The Transcontinental Arch acts as the southern boundary. The Cedar Creek anticline separates the Bighorn Group from equivalents in the Powder Basin (Gerhard et al., 1990). Emergence of the Sioux Arch separated it from possibly equivalent sediments to the east: the Viola Formation in Nebraska (Figure 1.7). Other equivalent remnants to the Bighorn Group dolomites include the Beaverfoot in British Columbia, Saturday Mountain in Idaho, Fish Haven in Utah, Hanson Creek in Nevada and Montoya in New Mexico (Patterson, 1961). Subsidence of the Williston Basin, which began during the late Cambrian, may have been due to continental rifting (DeRito et al., 1983) or renewed movement of Precambrian transform structures (Kent, 1987). Subsidence has been episodic, with major periods of relatively high subsidence (reactivations) occurring during the Devonian and Cretaceous periods (DeRito et al., 1983).

Several intrabasinal structures (Figure 1.6) affected sedimentation within the Williston Basin (Haidl et al., 2000; Ruzyla and Friedman, 1985; Kent, 1972). The Nesson and Cedar Creek Anticlines are large fault bounded anticlinal features. The emergence of the Nesson Anticline during Tippecanoe deposition is inferred by the thinning of the Red River 'C' Anhydrite Member over it. Kent (1972) found that the Nesson and Cedar Creek Anticlines have a direct influence on the distribution of pre-Mississippian oil pools in southern Saskatchewan, northeastern Montana, and northwestern North Dakota. Large structural features in the Williston Basin have influenced Ordovician sedimentation; whereas, the smaller ones appear to have had a greater influence upon porosity development (Gerhard et al., 1990). Kohm and Louden (1978, 1979) inferred that the porosity trends in the Red River Formation ran parallel to Northeast-Southwest trending lineaments in eastern Montana and western North Dakota. The Northeast-Southwest trending bands of porous dolomite in the 'C' Laminated Member (Lake Alma Dolomite of the Herald Formation) alternate geographically with bands of porous dolomite in the 'C' Burrowed Member (Yeoman Formation), and their distribution is thought to be caused by fractures or

lineaments in the basement rock. Potter and St.Onge (1991) also found a dependence between the structural elements and the distribution of oil pools.

Although the structure of the entire Yeoman (Red River) Formation is relatively undisturbed (Figure 1.8), the distribution of oil pools has also been affected by structural elements. Haidl et al. (2000), as well as Kreis and Kent (2000) have recently examined the relationships between the topography on the Precambrian surface and distribution of Yeoman (Red River) oil pools in southern Saskatchewan. Figure 1.9 illustrates the apparent distribution of Yeoman (Red River) oil pools above areas where the underlying Cambrian-Ordovician Deadwood Formation is anomalously thin. This relationship supports the findings of Kent (1972), Potter and St.Onge (1991), and Gerhard et al. (1990) that the reactivation of Precambrian surfaces has controlled Red River sedimentation and thus the location of Red River oil pools. They have reaffirmed those earlier observations with additional data points, and newer gravity, aeromagnetic and seismic data.

Sedimentology and Depositional Environment of the Yeoman and Herald Formation Carbonate-Evaporite Cycles

The lithologic characteristics of the Bighorn Group are indicative of deposition in a shallow epicontinental sea. It has generally been agreed upon that the Yeoman (Red River 'C' Burrowed Member) Formation was deposited in a low energy, subtidal environment (Kohm and Louden, 1978; Longman et al., 1983, 1987; Kent and Haidl, 1999). Subtidal deposition is indicated by: uniformity in the thickness and lithology across the basin; absence of supratidal features such as desiccation cracks, iron staining and paleosols; the dominance of mud-supported carbonates and general lack of clastics. The lack of faunal diversity suggests that the Williston Basin may have been partially restricted. Some believe that the presence of widespread organic-rich beds (kukersites) in the uppermost Yeoman (Red River 'C' Burrowed Member) Formation indicate episodes of severe restriction (Kendall, 1976; Carroll, 1978, 1979).

The three Red River carbonate-evaporite cycles (C, B and A), each consisting of a burrow-mottled limestone, a laminated dolomite, and a capping anhydrite, are generally given two different environmental interpretations. The classic interpretation is that of a shallowing upward sequence, which has been applied to similar sequences in other basins. The second interpretation is one that consists entirely of subtidal deposition, but with increasing restriction of the basin.

Kent (1960), Kendall, (1976), Kohm and Louden (1978, 1979), and Longman et al. (1983, 1987) prefer the subtidal model for the deposition of the Red River 'C' cycle (Yeoman Formation and Lake Alma Member of the Herald Formation), as they found little evidence of intertidal or supratidal features, especially in the anhydrite members. The thickness and widespread nature of the thick cycle members further supports this interpretation. There appears to be no interbedding of the otherwise suggested subtidal, intertidal and supratidal sediments. They believe if each cycle were to represent a single progradational event, then features such as interbedding should be present. Also, if the anhydrite caps are

of supratidal origin, their boundaries should extend beyond the carbonate units. Furthermore, these anhydrite members should also be interbedded with the carbonate unit and continental red beds, but these Ordovician anhydrites are in the center of the basin and red beds are absent at the peripheries of the basin. The aforementioned authors found no evidence for subaerial exposure. The structure of laminated carbonates is not consistent with intertidal and supratidal interpretation. No algal mat remnants have been identified in the laminated units. Finally, the Red River anhydrite units do not have the structure of supratidal anhydrites. Rather they are displacive nodular anhydrites suggesting that they were subaqueously deposited.

The interpretation, that these sediments represent a shallowing upwards subtidal to supratidal cycles, is less common and restricted to the southern portion of the Williston Basin (Carroll, 1978, 1979); Ruzyla and Friedman, 1985; Clement, 1985). Carroll believes the anhydrite units represent sabkha deposits. Due to the presence of desiccation cracks in the laminated units of North Dakota, he believes that they are of intertidal and supratidal origin. Clement as well as Ruzyla and Friedman, found criteria which supported this model. They found cross-bedding and interbedding between the laminated anhydrite and dolomite mudstones near the Cedar Creek Anticline. Clement (1985) recorded some desiccation features. The two models for the depositional environment of the Red River cycles need not be exclusive of each other and only a study, which encompasses core from throughout the Williston Basin, will be able to solve the problem. Neese (1985) found evidence for a depositional environment, which incorporated both models. Core data from the North Sheridan County was interpreted to indicate that the Red River 'C' interval represents both a shoaling and brining upward sequence (Neese, 1985), and indeed the two need not be exclusive of each other.

Fauna

The fossil assemblage of the Yeoman formation varies slightly throughout the Williston Basin. The following fossil assemblage is most commonly observed in core: tabulate and solitary rugose corals, nautiloids, brachiopods, bryozoans, echinoderms, stromatoporoids and gastropods (Haidl et al., 1997; Kendall, 1976). Others also noted ostracods and trilobites (Longman et al., 1987; Kent and Haidl, 1999). In southern Saskatchewan, the Yeoman has a restricted faunal assemblage consisting of large gastropods (macluriids), solitary rugose corals, and several types of brachiopods. Echinoderm debris occur throughout, whereas stromatoporoids, bryozoans and bivalves are present but never abundant (Baillie, 1952). *Receptaculites*, which are abundant in the Tyndall limestone, are absent here. The kukersites, which are organic rich intervals, with greater than 90% kerogen content by volume (~ 35 wt % carbon), are primarily made up of an algal microfossil *Gloeocapsomorpha prisca* believed by Canter (1998) to represent flooding surfaces. Their origin is the focus of Chapter 3.

Ichnology

Most studies of the Yeoman Formation in the Williston Basin have interpreted the mottling to be the result of *Thalassinoides*-like burrows. (Kendall, 1976, 1977; Kissling, 1999; Canter, 1998; Qing et al., 2001). Dolomite mottling is common throughout the Yeoman (Red River) Formation and some may indeed represent *Thalassinoides*. A second generation of smaller burrows has been observed within the *Thalassinoides*. These burrows have been interpreted as being of the ichnogenus *Planolites*. Kissling (1999) described *Thalassinoides* in the Lower Red River (Yeoman) Formation as three-dimensional anastomosing features with 2 millimeter diameters. He refuted the hypothesis that their origin was due to successive deposit feeders, based on to the following evidence: the irregularity of the burrow mottles, paucity of back-fill spreite and the unlikelyhood of deposit feeding at such a depth as assumed for deposition. He believed that the burrows were formed by filter feeders, such as polychaetes or decapod crustaceans. The above studies however are not undisputed in their description of the ichnology of the Yeoman Formation. The burrows described by Kissling do not agree with the generally accepted description of *Thalassinoides*, By definition, their diameter ranges from 1 to 20 cm (Häntzschel, 1975). Others have suggested that the mottles are in fact diagenetic haloes around narrower burrows of either *Planolites*, *Chondrites* or *Palaeophycus* (Carroll, 1978, 1979; Gingras, 2000). Although Kendall (1976) does mention they may be diagenetic replacement with the replacement proceeding away from the burrows, their interpretation as *Thalassinoides* has been preferred. Some of the *Thalassinoides* interpretations may be due to the fact that some burrows described from a Ordovician Swedish limestone are classified as *Thalassinoides*, although they do not have a diameter of 1 cm (Bromley, 1996). This was apparent in Kissling's (1999) description of *Thalassinoides*.

Diagenesis

Diagenesis has a complex control on porosity and permeability. The diagenetic history of the Bighorn Group has been extensively studied throughout the Williston Basin to evaluate the economic potential of these carbonates. These controls are discussed in Chapter 5, which focuses on burrow-related dolomitization and the diagenetic history of the Yeoman Formation.

Exploration and Production

Successful exploration and production of the Yeoman and Herald (Red River) Formations south of the US-Canada Border, prompted exploration on the Canadian side of the Williston Basin. This has resulted in the discovery of several fields have been found since the 1970's. Potter and St.Onge (1991) believe there is a link between diagenesis and basement faulting. Dolomitization fairways with the increased porosity parallels Northeast-Southwest trending basement lineaments. In the Minton Pool of southern Saskatchewan, much of the oil is trapped in structural highs related to Phanerozoic movement of

the Precambrian basement blocks (Potter and St.Onge, 1991; Haidl et al., 1997). Some stratigraphic and structural/stratigraphic traps are also encountered. Haidl et al. (1997) suggested that micro-fractures associated with these larger fault systems commonly enhance the permeability. Diagenesis also influences trapping as dolomitization is the main control on secondary porosity.

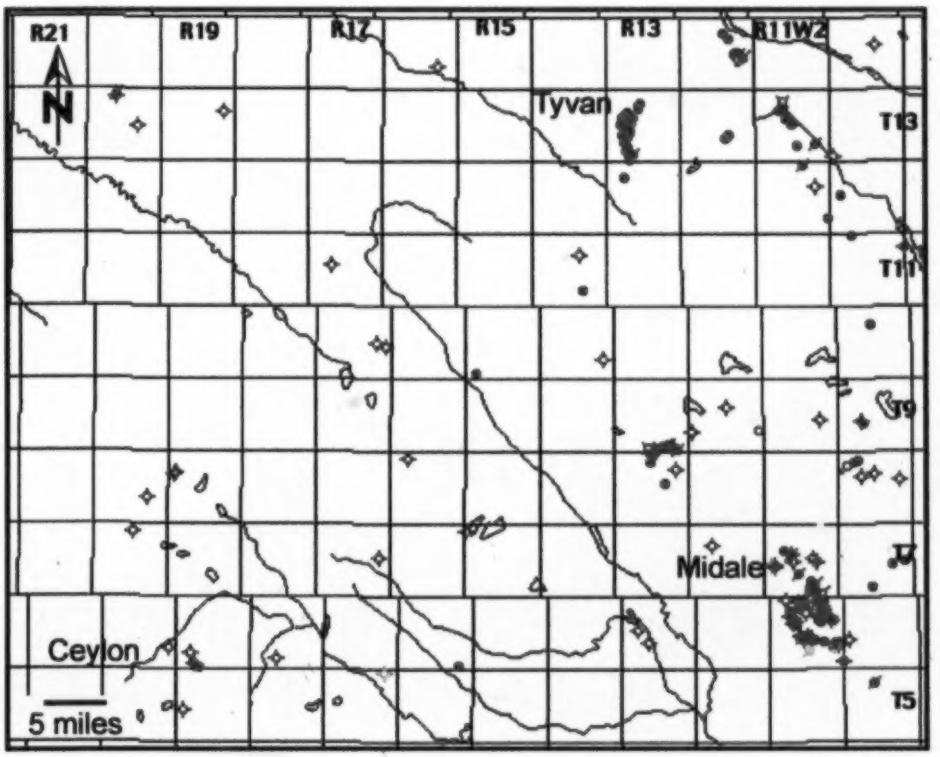
In general, the Red River 'C' Burrowed Member (Yeoman Formation) is a better reservoir than the Red River 'C' Laminated Member (Kohm and Louden, 1978; Clement, 1985); however, in some areas the inverse is true (Neese, 1985). At the Midale pool in southern Saskatchewan, the best reservoir is contained in the transitional zone between the 'C' Laminated and the 'C' Burrowed (Basal Lake Alma) Members (Canter, 1998).

The kukersites in the upper third Yeoman Formation (Red River 'C' Burrowed Member) have sourced the Yeoman/Red River Reservoirs (Kohm and Louden, 1878; Kendall, 1976; Fowler, 1992). These kukersites are considered to be the source rocks for most of the produced Ordovician oil in the Williston Basin (Kendall, 1976; Kohm and Louden, 1978; Osadetz and Snowdon, 1995; Haidl et al., 1997). The underlying Winnipeg shales are believed to have sourced some of the Yeoman (Red River) hydrocarbons (Ruzyla and Friedman, 1985; Clement, 1985). Analyses of thermal maturation have dated maturation of Ordovician source rocks and migration of the oils to late Cretaceous, from both the Red River kukersites and the Winnipeg shales (Ruzyla and Friedman, 1985; Clement, 1985).

1.4 Concluding Remarks

Many sedimentologic and diagenetic aspects of the Yeoman Formation have been studied to date. As is common, exploration and production drive many of the studies, thus core data is generally limited to producing intervals of the Yeoman Formation. Outcrop is readily available, but until its correlation with subsurface members is established, its usefulness is limited. Although the ichnology was discussed in many studies, a detailed description of the biogenic sedimentary structures is not yet available. Therefore, the trace fossils of the Yeoman Formation are the focus of this study. Their use in examining the origin of kukersites, as well paleoecological changes throughout Yeoman deposition are discussed. Since the most prominent fabric of these sediments is the burrow-related dolomite mottling, the diagenetic history and the formation of these dolomite mottles are also examined. The objective of this study is to add another dimension to the understanding of these Upper Ordovician sediments of the Williston Basin.

Figure 1.1 Study Area with Three Examined Oil Pools: Midale, Tyvan and Ceylon



Note: See Appendix 1 for a detailed map of each oil pool.

Figure 1.2 Stratigraphic Nomenclature for the Bighorn Group

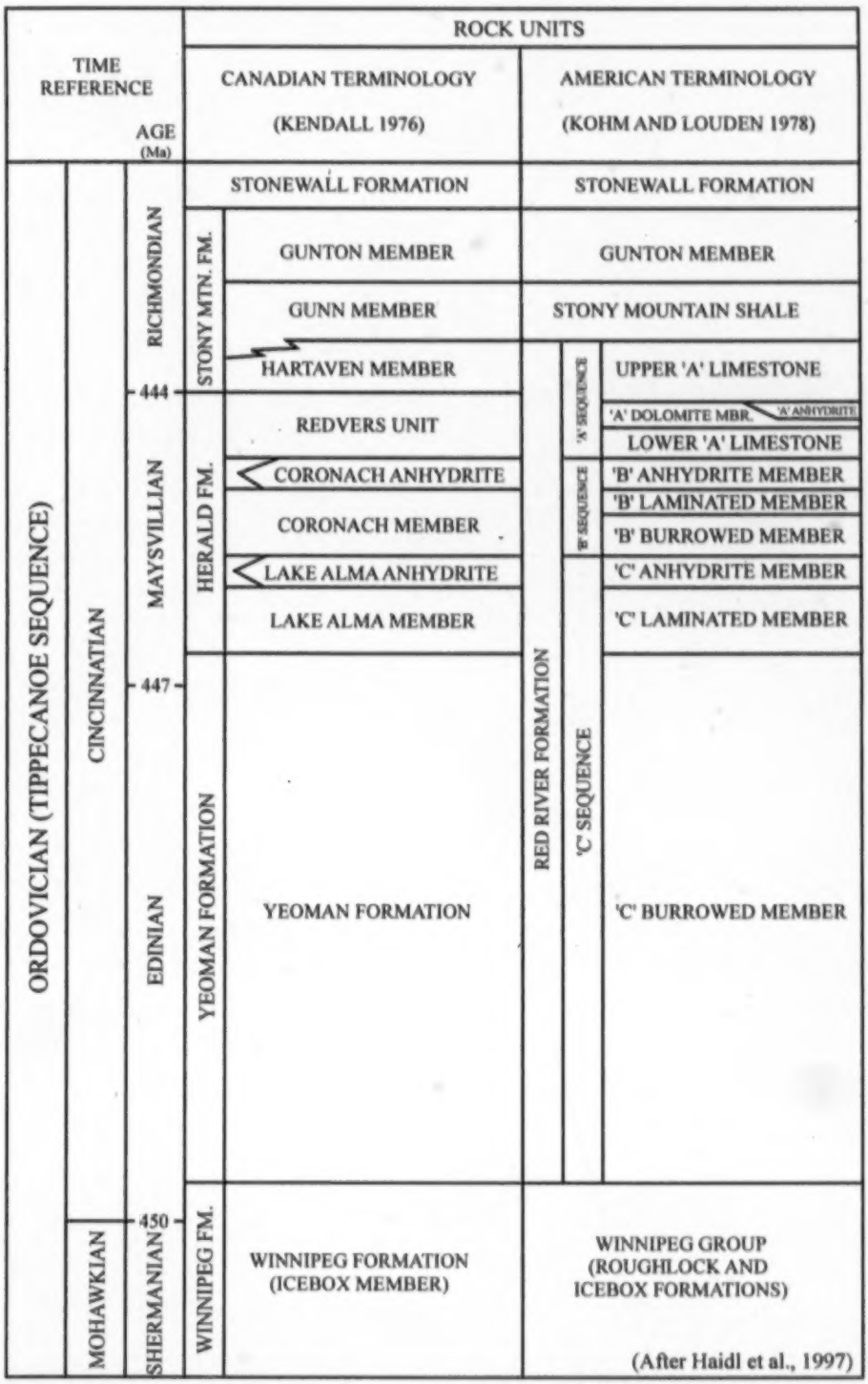
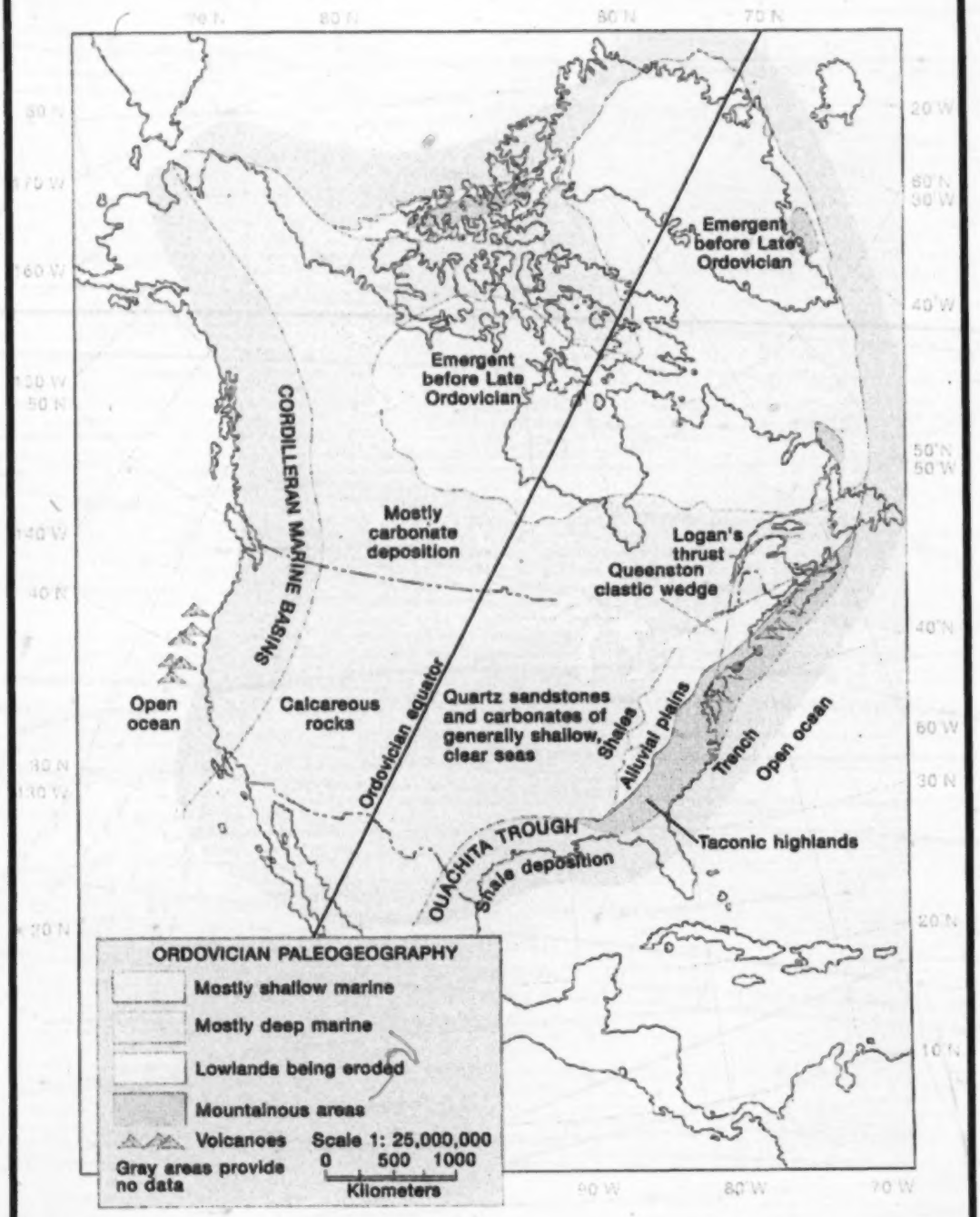


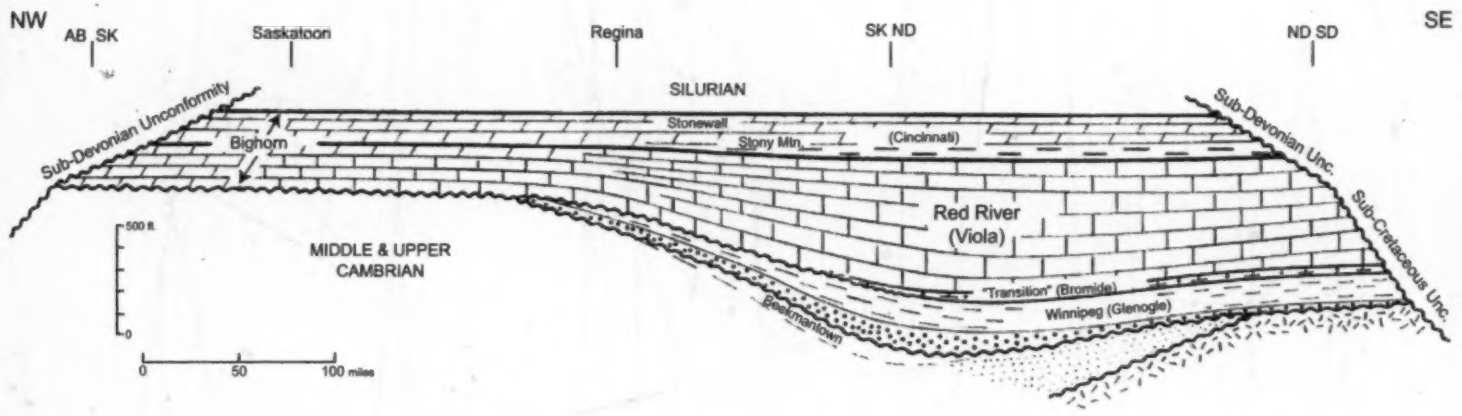
Figure 1.3 Paleogeographic Map of the Ordovician in North America



(Levin, 1994)

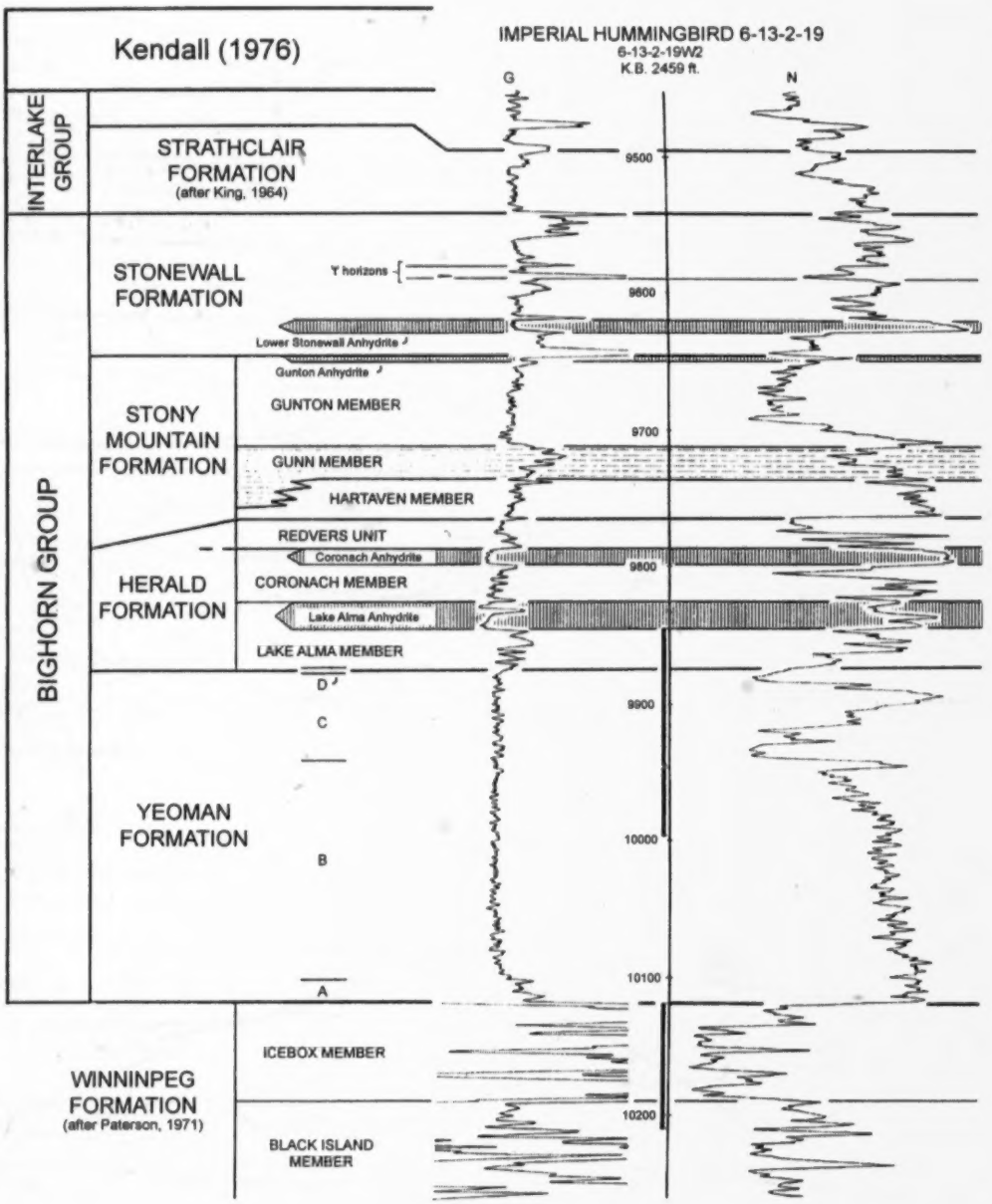
Figure 1.4

Cross-Section of the Ordovician in the Williston Basin



(After Patterson, 1961)

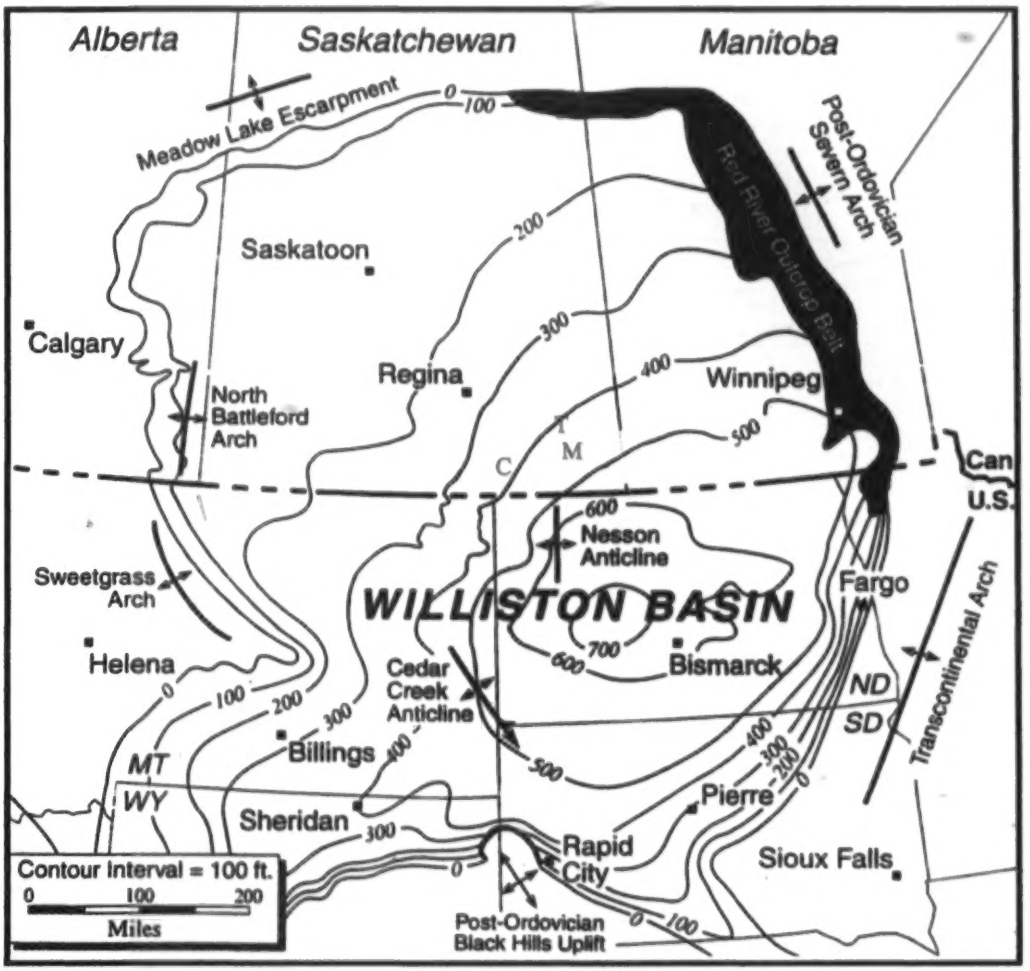
Figure 1.5 Kendall's Subdivisions of the Bighorn Group in Southern Saskatchewan



D: Basal Lake Alma Member of the Herald Formation (Kent and Kissling, 1998).

(After Kendall, 1976)

Figure 1.6 Regional Extent of the Bighorn Group in the Williston Basin

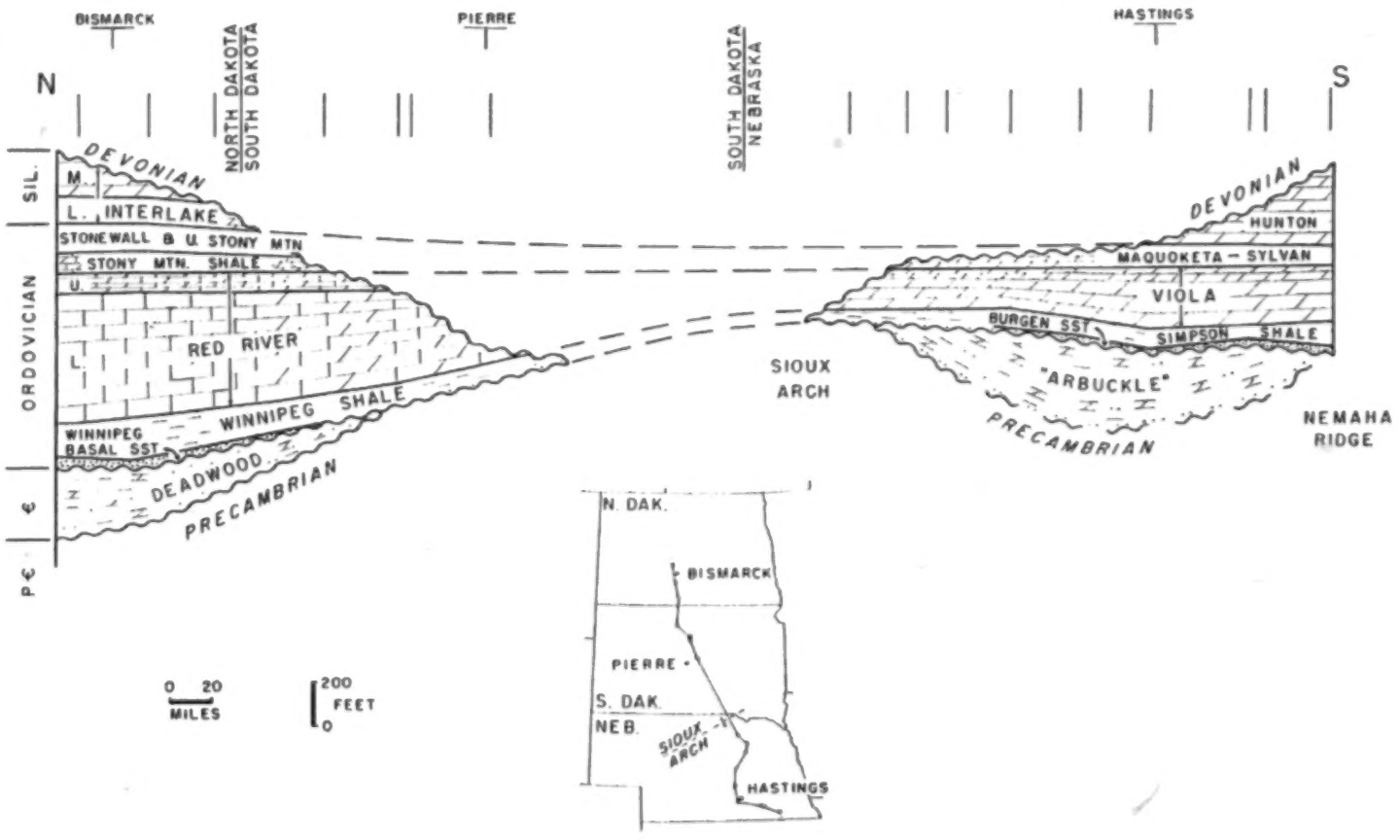


Isopach of the Upper Ordovician Red River strata and present day structural elements of the Williston Basin. M: Midale Pool. T: Tyvan Pool. C: Ceylon Pool.

Location of Figure 2.5, *Thalassinoides* in Yeoman/Red River Formation outcrop near Flin Flon, Saskatchewan.

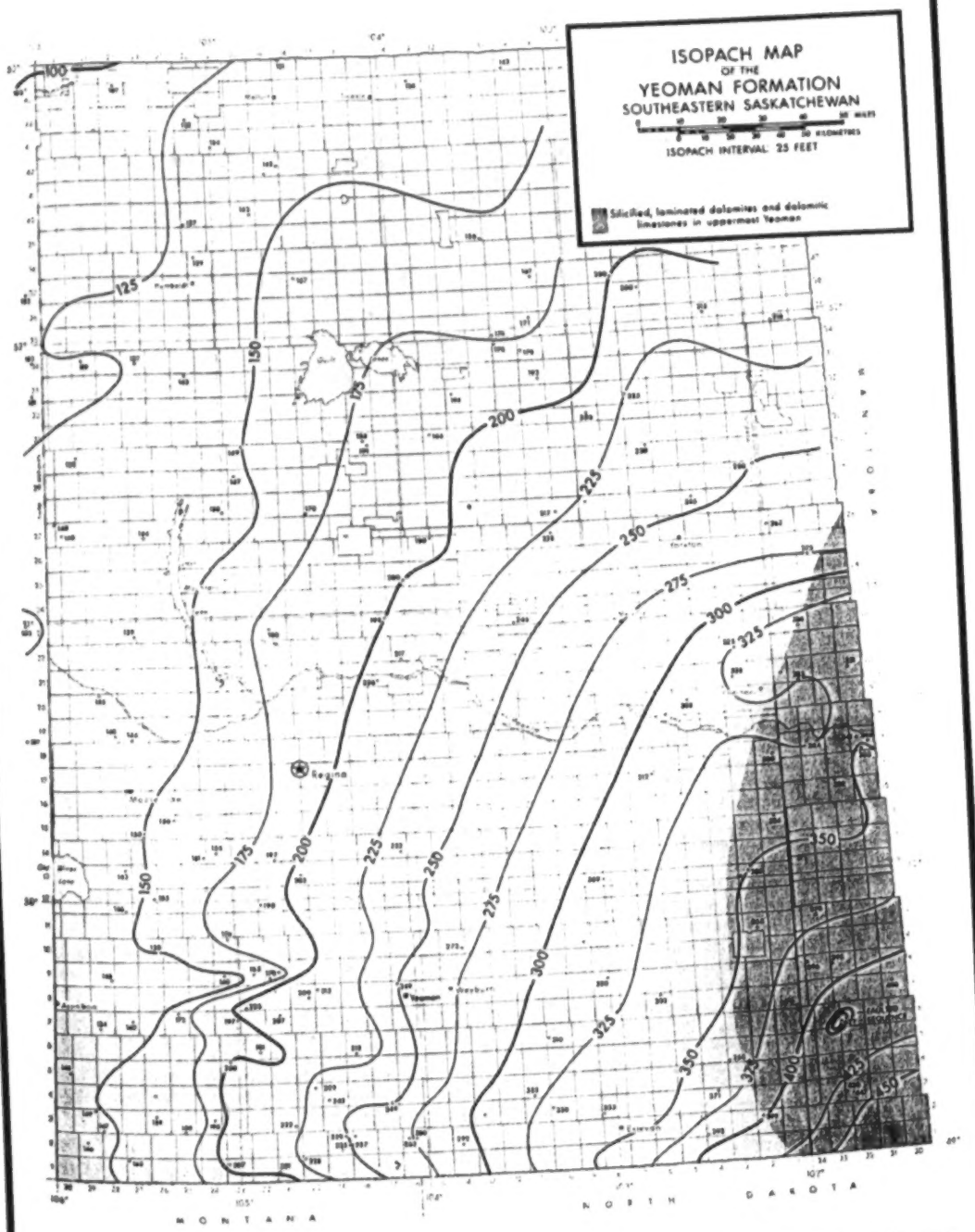
(After Haidl et al., 1997)

Figure 1.7 Cross-Section of Ordovician Sediment Over the Sioux Arch



Cross-section illustrates former stratal continuity of Ordovician sediment over the Sioux Arch. (Patterson, 1961)

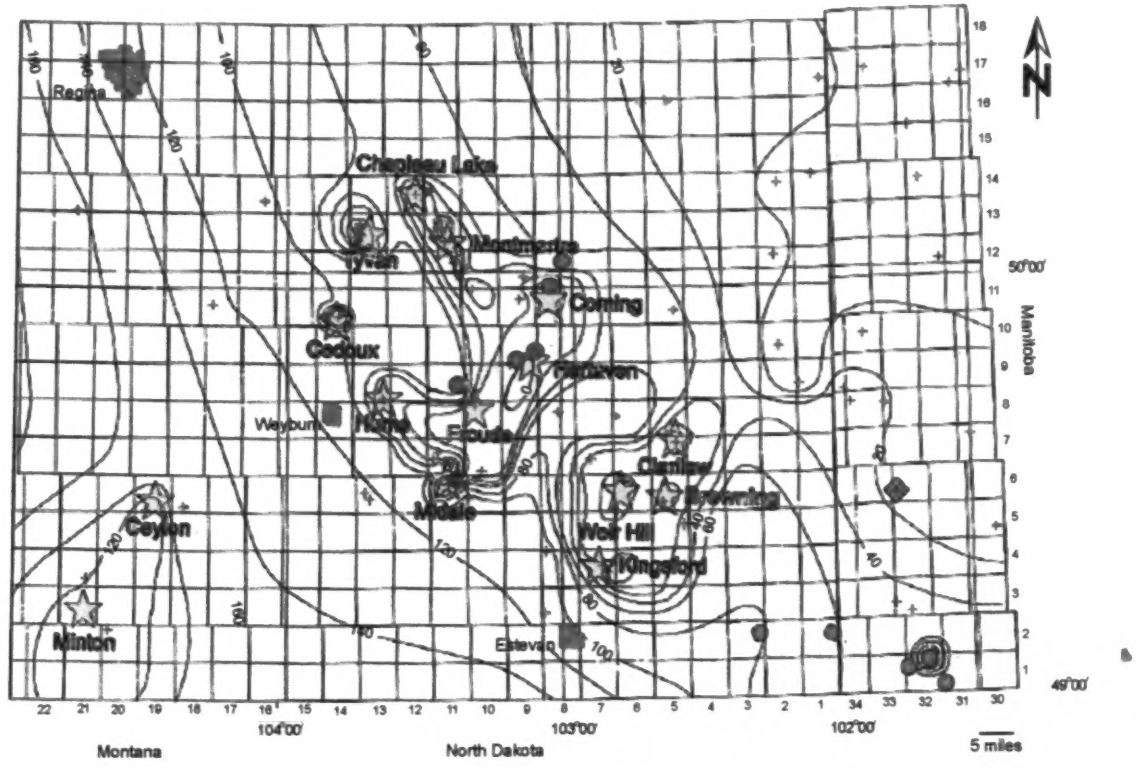
Figure 1.8 Isopach of Yeoman Formation in Southeastern Saskatchewan



Structure of the Yeoman Formation is relatively undisturbed. Sediments thin almost uniformly away from the southeast of Saskatchewan.

(Kendall, 1976)

Figure 1.9 Isopach of the Deadwood Formation in Southeastern Saskatchewan



Distribution of the Deadwood strata reflects local topographic relief on the Precambrian surface during Deadwood deposition and/or uplift and subsequent erosion prior to the deposition of the Winnipeg Formation. Note the common association of Red River (Yeoman and Basal Lake Alma Member of the Herald Formation) oil pools with areas of zero or anomalously thin Deadwood, coincident with Precambrian highs. Countour interval is 20 m. (Haidl et al., 2000).

CHAPTER 2. TRACE FOSSILS OF THE YEOMAN FORMATION

2.1 INTRODUCTION

Recognition and classification of trace fossils in the Yeoman Formation of Southeastern Saskatchewan is impeded by the complex diagenetic history of these sediments. Since many primary characteristics of deposits greatly influence the diagenesis, the distinction between sedimentary and diagenetic fabrics can be difficult. This problem presents itself clearly in an examination of the trace fossils of the Yeoman Formation, which is characterized by conspicuous dolomite mottling. To date, it remains debatable whether these represent *Thalassinoides* or sediment dolomitization around smaller, causative burrows. The majority of ichnological studies were done in clastics or chalks (Kennedy, 1975), and since such sediments are so different from Paleozoic platform carbonates, their methods are commonly difficult to apply. The purpose of this chapter is to describe the trace fossils of the Yeoman Formation, and to explore their potential usage in determining changes throughout the deposition of this thick platform carbonate. Although diverse feeding structures are represented in these sediments, it appears that the benthic fauna was restricted, but capable of adapting behaviour to changes in sedimentation, water energy, oxygenation and nutrient supply.

2.2 RECOGNIZING AND CLASSIFYING TRACE FOSSILS IN CARBONATES SUBJECT TO HEAVY DIAGENESIS

Trace fossil classification primarily focuses on morphology; aspects of secondary consideration include such factors as burrow lining, contrast between the burrow fill and matrix sediment, as well as the host sediment and nature of packing of grains. Not surprisingly, many trace fossils were originally described in clastic sedimentary rocks, where the nature of the grains are much less influenced by recrystallization, replacement and fabric destructive diagenesis. In contrast, diagenesis can alter the nature of a carbonate rock so much so that the original sedimentary fabric and even mineralogy can no longer be determined with certainty. While it is true that many trace fossils owe their preservation and recognizability to diagenetic fabrics, only to a point will it serve to enhance their appearance. Beyond this point, destructive processes of recrystallization, replacement and commonly extensive dissolution take over, and burrows and all primary constituents fade from recognition.

Increased burrow densities can make discrete trace fossils difficult to discern, as can the absence of a burrow lining or the insufficient contrast between burrow fill and host sediment (Fürsich, 1975). Preservation is also skewed in favour of the latest and deepest "tier" of burrowing, since it has the highest preservational potential (Bromley and Ekdale, 1986). All things considered, the greatest limitation of examining the Yeoman trace fossils, is the unavailability of data. Core description rarely allows a 3-dimensional view of trace fossil morphology. Weathering exposures, which have provided samples for

many ichnological studies are not available and one must infer from repeated patterns and observations what may be the 3-dimensional shapes of the observed biogenic sedimentary structures. Bedding planes and contacts are a rarity in the Yeoman Formation where the overlying and underlying sediments are similar, and it is most commonly only firmgound and hardground surfaces that are recognizable. Bedding plane recognition is also reduced by abundant pressure solution. Stylolites and solution seams commonly form at contacts between differing substrates, thus preventing the recognition of interface trace fossils, such as tracks and trails of benthic epifauna.

Taken together, the above factors not only make it difficult to accurately determine substrate controls, but also impede the interpretation of the behaviour of the trace producer. Where the contrasting nature of the burrow fill and matrix determine the feeding behaviour of the trace producing organisms (Kotake, 1989), diagenesis can destroy this crucial information.

With these limitations in mind, Yeoman trace fossils are classified keeping the following in mind. Original fabrics are inferred by examining corresponding intervals. The zone least affected by diagenesis is taken to most closely resemble original fabric and mineralogy. Locally, present day fabrics proved to be useful, since rocks of differing original mineralogy and fabrics may have undergone different diagenetic pathways. For example, increased porosity or crystal size in a burrow fill may be indicative of a syndepositional contrast between the burrow fill and the host matrix. Comparison with studies of other carbonates, especially age equivalent rocks, are useful in 'seeing' how others dealt with these complications. Finally, it must be noted that since a freshly slabbed core surface and outcrop are not readily available, the more distinct trace fossils may skew the observations concerning the trace fossil assemblage and abundance. Where possible, the trace making behaviour is discussed as well, as it will be important in subsequent chapters in the discussion of ecological implications of trace fossil associations. Due to the aforementioned difficulties in trace fossil identification, trace fossils are classified only on the generic level. Details to determine trace fossils species are not readily available in this core study. The horizontal expression of individual trace fossils is limited by core diameter.

2.3 *PALAEOPHYCUS* AND *PLANOLITES*

These morphologically simple burrow types are the most common in the Yeoman Formation and commonly co-occur in all the different Yeoman fabrics. They are discussed together here for two reasons. First, the distinction between these two trace fossils has caused extensive debate even in examination of clastic sedimentary rocks. The author must refer the reader to extensive discussions on the topic in: Pemberton and Frey (1982), Keighley and Pickerill (1995), as well as others. Second, these are the most common burrows in the Yeoman Formation and sometimes the distinction is problematic and may not even be possible.

Description of Ichnogenus *Palaeophycus* Hall, 1847:

Burrow orientation is dominantly horizontal, with minor subhorizontal to (sub) vertical components. Similar vertical, straight burrows, which are found to be occurring alone, are classified as *Skolithos*. Burrows are straight to curved, and circular to elliptical in cross-section (Figure 2.1). *Palaeophycus* are rarely branched, and the type of branching is not discernible. The burrows have regular, smooth external ornamentation. The linings, which contain organic matter, vary in thickness, and locally appear annulated. The linings comprise a variety of macerals (*Gloeocapsomorpha prisca*, spiny, acantomorphic acritarchs, Leiosphaeridiai) and zooclasts (scolecodonts and chitinizoans) and in Facies 1 and 2, but consists predominantly of *G. prisca* in the other facies (Figure 3.9, 3.10). Commonly, burrow linings also consist of algal detrinite and/or bitumen. *Palaeophycus* generally have a homogeneous internal fill. Burrow fill, however, may be recrystallized as saddle dolomite or coarser dolomite; alternately the fill may be dissolved and the burrow core hollow. Re-burrowing by *Planolites* is observed (rarely). Diameter is constant along burrow axis, ranging from < 1 millimeter in some intervals to nearly 5 millimeters. Burrow density depends on facies. The fill, where unaltered, is similar to the host rock. However, it is rarely undolomitized. Interestingly, some undolomitized *Palaeophycus* do occur amidst dolomitized *Palaeophycus*. The microfossils in their linings, unfortunately due to lack of prepared samples, were not examined. Burrows generally have good to excellent preservation, and it would appear that the organic-rich lining of the burrows has aided in both preservation and recognition of these burrows.

Discussion:

Palaeophycus is distinguished from *Planolites* primarily by wall linings and the character of the burrow fills. Although *Palaeophycus* are found in most of the Yeoman intervals, *Palaeophycus* are found more commonly in intervals rich in allochems, but depleted in dispersed organic matter/kerogen and mud. Infills of *Palaeophycus* represent passive, gravity-induced sedimentation within open lined burrows (Pemberton and Frey, 1982), although this can not be determined if true for the Yeoman Formation. *Palaeophycus* are generally interpreted as the open dwelling burrows of suspension feeding or carnivorous animals (Pemberton and Frey, 1982). The presence of collapse structures in the Yeoman burrows supports this interpretation, as do the presence of geopetal fills. The primary objective in constructing dwelling burrows is protection, therefore intervals dominated by domichnia are thought to suggest well illuminated, shallow water deposits where predation is greatest. In modern environments, dwelling burrows are pretty much restricted to shallow, well-illuminated intervals (Schäfer, 1972). Possible trace makers may be sipunculid, annelid, enteropneust or polychaete worms. Further examination of scolecodonts in association with these burrows might help identify behaviour of trace making organism, since scolecodont shape reflects feeding behaviour (predation vs. scraping). Their presence is notable and certainly merits further investigation, since scolecodonts, due to their sensitivity to diagenesis, are rarely found in marine sediments with many trace fossils (Schäfer, 1972).

Description Ichnogenus *Planolites* Nicholson, 1873:

Planolites generally are preserved as horizontal to subhorizontal intrastratal burrows (Figure 2.2). They are rarely branched, but are found crosscutting and interpenetrating each other. Burrow diameter is unaltered by branching. These burrows are straight to curved, and sometimes meandering. Cross-sections are circular to elliptical, the latter resulting from both compactional flattening or oblique sectioning of the burrow. Burrows are smooth-walled, and their fill is homogeneous. Rarely they exhibit a meniscus structure and may contain secondary *Planolites*, of equal or smaller diameter. Burrow diameters are found ranging from < 1 millimeter (discernible only microscopically) to almost 1 centimeter. The thickness is generally constant along the burrow length, however the absolute length of burrows is indeterminable. Burrow density is dependent on facies, generally being higher in muddier substrates. The fill is different from host rock as it generally contains less dispersed organic matter and kerogen, but it may also be dolomitized, or contain a different dolomite type than the host rock. The fill may contain a contrast in allochem abundance (greater or smaller) or the burrow may contain oriented/structured allochems. These last few criteria generally require thin sections for recognition.

Discussion:

Planolites are found in all the Yeoman Facies, but in variable abundance. They may occur as secondary burrows, in *Thalassinoides*, *Asterosoma*, *Rhizocorallium*, *Trichophycus* or alone. *Planolites* may occur associated with *Chondrites*, or as a monospecific assemblage. *Planolites* is distinguished from *Palaeophycus* primarily by having unlined walls and burrow fills differing in texture from that of the adjacent rock. Fills may differ in fabric, composition and color as well. Infills of *Planolites* represent sediment processed by the tracemaker, especially through deposit-feeding activities of mobile endobionts (Pemberton and Frey, 1982). In the Yeoman specimens, the local development of weak menisci further supports an active back-fill interpretation. Interpenetrations and re-burrowed segments of *Planolites* are easily confused with true branching, which is comparatively rare. Petrographic investigation is commonly required for distinction, and that is not always possible. Since the *Planolites* animal re-burrowed numerous other kinds of traces, such pre-existing traces presumably contained enhanced nutrient levels such as dispersed organic matter and/or represented an easier path for new burrowing activities. The former cause for these secondary burrows seems to be valid since the fill of the last tier of burrows has the lowest content of organic matter. *Planolites* are generally interpreted to represent deposit-feeding behaviour. Preservation of mucous linings in sediments, having undergone such extensive diagenesis as the Yeoman Formation, is unlikely, therefore some burrows may be incorrectly classified as *Planolites* due to an apparent lack of burrow lining.

Burrow Lining or Diagenetic Halo?

Central to the diagnosis of these forms is the presence or absence of wall linings (Frey and Pemberton, 1982). Diagenetic haloes can readily be mistaken for linings in a megascopic examination. Thin

sections may be required to differentiate the two. Burrow lining is indicated by a concentration of organic matter and/or bitumen, evidence of spreite at burrow wall, or where there is a thick wall with contrasting abundance of organic matter. Increased porosity along burrow walls is taken to suggest a dissolved lining or mucous layer. Diagenetic haloes are in fact very common in the Yeoman Formation and range from less than 1 millimeter in thickness to greater than 1 centimeter in thickness. Most burrowing organisms secrete some mucus or residue when burrowing through sediment (Schäfer, 1972; Bromley, 1996), and this mucus commonly acts as the catalyst for the formation of diagenetic haloes. Keighley and Pickerill (1995) suggested that a burrow lining might be inferred if the diagenetic halo extends from the burrow boundary into both the burrow fill and the host lining. In the Yeoman Formation this criterion failed to prove useful, as the fills of both lined and unlined burrows are commonly dolomitized.

Determining Nature of Original Burrow Fill

The secondary ichnotaxobase is the burrow fill. In carbonate sediments like the Yeoman Formation, this proves to be problematic because diagenesis has altered the sediments. It is a comparison of the inferred burrow fill and matrix at the time of sedimentation, and not the present day nature of these sediments that must be used as the ichnotaxonomic criterion. Where dissolution of the burrow core has occurred or dolomitization and recrystallization has been fabric destructive, the interpretation can lead to mis-interpretations and incorrect classifications. This approach is viable only if the burrow fill and matrix remain a reflection of their primary textural state.

Branching or Crosscutting Burrows?

It must be noted that the crosscutting of burrows can easily be confused with true branching. Evidence to truly distinguish branching from crosscutting burrows may be problematic, and in some cases it may not even be possible (Keighley and Pickerill, 1995). This holds true for the Yeoman Formation, where distinction between abundant *Planolites* and *Chondrites* is arbitrary (see facies 8).

2.4 Composite Burrow Systems

It is common in ichnological studies to classify all biogenic sedimentary structures as discrete trace fossils, but in doing so one may create a false impression of a diverse benthic community. In many intervals of the Yeoman Formation, composite burrow systems are identified which display a combination of behaviours, such that classification as a single burrow type is impossible. Discrete burrows, which in addition to *Planolites* and *Palaeophycus* are commonly part of this system, will be discussed in subsequent sections.

Description of Composite Burrows:

These complex biogenic sedimentary structures are simply or multiply lined, anastomosing burrow systems, which exhibit branching and crosscutting, evidence of U-shaped portions, spreite resulting

from shifting of the burrow system, as well as, spreite in the burrow fill (Figure 2.3, 2.4). The fill is generally dolomitized mudstone, therefore the contrast between the host sediment and burrow fill may only be a result of diagenesis. The organic-rich linings may be thin or up to several millimeters, and commonly resemble concentric linings of *Cylindrichnus concentricus* described by Goldring (1996) and Fürsich (1974b). These linings are dominantly comprised of organic matter: dominantly disseminated A and B *G. prisca* alginite where the organic matter is not degraded. Amorphous organic matter and algal detrinite is also common in burrow linings. Macerals and zooplankton observed in *Palaeophycus* linings are rarely observed in these burrow linings. Other portions of the burrow systems exhibit characteristics of *Phycodes*, *Asterosoma* and *Rhizocorallium*. These burrows systems also occur in close association with the aforementioned burrows. The burrow diameter of the original, and later burrows remains comparable. Burrow diameter does not change with branching. Rarely, a larger diameter *Planolites* crosscuts a smaller, lined burrow.

Discussion:

The concentric linings are believed to have been formed by the construction of a multi-layered wall, whereby the organism added successive walls pushing former layers outwards (Aller and Yingst, 1978 *in* Goldring, 1996). Of Goldring's three hypotheses for formation of concentrically lined burrows, Aller and Yingst's method seems most likely because the material lining the burrows appears to have been introduced into the burrow; i.e. most of the lining material is planktonic and absent from the matrix sediment. These complex feeding systems may have initially served purpose as the dwelling burrows of filter-feeding or carnivorous organisms. Once the environmental conditions changed, perhaps there was a decrease in the nutrient availability in the water column, these organisms shifted their behaviour to exploit organic matter and organic detritus they had used to line their burrows. The last tier of *Planolites* and/or *Chondrites* indicates deposit-feeding activities. One needs not invoke changes in environment as the cause of changes in feeding behaviour, because organisms are also known to change their feeding patterns, diurnally and seasonally (Schäfer, 1972; Hummel, 1985).

Consistent burrow diameter throughout these systems suggests that all the tiers of these burrows were created by the same or similar organisms; thus, although diverse feeding patterns are preserved, these systems may have been produced by a single or small group of organisms. Inferring that the suspension-feeding components of these composite burrows, and other suspension feeding burrows described from the Yeoman Formation were formed by a single species is consistent with Turpaeva's hypotheses (1957 *in* Walker, 1972) concerning trophic relationships of benthic fauna. Based on an examination of feeding ecology of modern benthic animals, she believed that one trophic group generally dominates a community, with the most dominant species belonging to one particular trophic group. This, she inferred, is characteristic of a stable community, in which the organisms attain a noncompetitive feeding arrangement. These composite burrows, which generally occur in intervals believed to coincide with *G. prisca* algal blooms (Chapter 3), presumably resulted from a species of polychaete dominantly consuming this algal

microfossil by a suspension-feeding mechanism. When conditions for successful filter feeding were interrupted, this worm-type organism might have adapted to a deposit-feeding behaviour that exploited the same algal microfossil, readily available in the sediment.

2.5 *THALASSINOIDES* EHRENBERG, 1944

The characteristic dolomite mottling, which is common in Lower Paleozoic platform carbonates, has commonly been interpreted as large branching burrow networks, either of the ichnogenus *Spongeliomorpha* or *Thalassinoides* (Zenger, 1992, 1996b; Zenger and Lemone, 1995; Myrow, 1995; Bottjer et al., 1984). This same interpretation has also been favoured for the dolomite mottles of the Yeoman Formation (Kendall, 1976, 1977; Canter, 1998; Kissling, 1999), although others believed that these mottles represent dolomitic haloes, which formed around *Planolites*, *Palaeophycus* and *Chondrites* (Carroll, 1978; Gingras, 2000). These two interpretations have different implications on the origin of the aforementioned burrows, which may be found in the dolomite mottles. According to the former model, they are secondary burrows, but the latter model infers they are causative burrows, which facilitated dolomitization of the matrix.

Due to this disparity in views with regards to the dolomite mottles, the dolomite mottles in the Yeoman Formation also required a close examination. According to Kendall (1977) three things remain unaccounted for if one interprets the mottles as diagenetic haloes:

1) The bimodal distribution of the mottle diameters (either a uniformity or a complete range of mottle diameters would be expected if the mottles represented diagenetic alterations around burrow centers).
2) The otherwise uniformity in the size of dolomite mottling throughout the thickness of the Yeoman – lower Red River interval and the whole of the Williston Basin (this uniformity suggests a burrow origin).
3) The mottles sometimes lack internal burrows, or they contain more than one burrow or burrows that are markedly eccentric. If dolomitization had proceeded uniformly outward from the burrow centers to generate cylindrical mottles, then mottles should always contain concentrically located burrows.

Gingras (2000) on the other hand, believed that since the dolomite mottles do not exhibit regular sharply demarcated boundaries and constant burrow diameters throughout the network, they did not represent biogenic sedimentary structures. His study, however, focused on the surface Tyndall Limestone, which although it can be examined on a larger scale in outcrop, displays some different sedimentary characteristics than the subsurface Yeoman Formation.

Thalassinoides-like burrows have been found in many Ordovician platform carbonates (Sheehan and Schiefelbein, 1984). Although the biological affinities of the organisms responsible for these networks has not yet been discovered, it seems quite plausible that at least some of the dolomite mottles in the Yeoman Formation should represent *Thalassinoides*. Lack of outcrop for the Yeoman Formation prevents a diagnosis based on plan geometry, i.e. determination of vertical and horizontal extent of these large characteristically branching networks. It must be noted that the mottle networks found in outcrops of both

the Tyndall Limestone and Lower Yeoman (Red River) Formation (Figure 2.5) greatly resemble other recorded Lower Paleozoic *Thalassinoides* (Sheehan and Schiefelbein, 1984; Watkins and Coorough, 1997). Although it may seem unlikely, one must note that the proper taphonomic conditions may not have existed to preserve the *Thalassinoides* in an identifiable form. Combined with destruction of many primary sedimentary structures by diagenesis, it remains impossible to determine with absolute certainty the presence of *Thalassinoides* in the Yeoman Formation. Therefore each interval of the Yeoman Formation need to be examined individually, often requiring comparison with the corresponding interval in a less diagenetically altered well.

Description of Ichnogenus *Thalassinoides* Ehrenberg, 1944:

Burrows are preserved intrastratally in vertical section. The orientation of their limbs is vertical and horizontal, although locally some are inclined, or portions of some are inclined. These burrows are branched, with both Y and T-shaped branching. Effect of branching on trace fossil size: diameter appears to remain constant along branches. Burrows are generally straight or slightly curved. Their cross-section is circular or elliptical. Burrow walls are smooth, regular and un-lined. Stylolites/pressure solution may often give appearance of thin organic-rich lining. Burrow fill is homogeneous, but it may contain secondary *Planolites* and *Chondrites*. Burrow diameter ranges from 5 millimeters to 2 centimeters. Burrow length is indeterminable. The burrow density is variable from few discrete *Thalassinoides* to *Thalassinoides* comprising about 50% of the rock volume. Burrow fill is commonly dolomitized, occasionally silicified, and there is contrast in allochem abundance relative to the host rock. *Thalassinoides* generally have poor preservation or recognition potential.

Collective Indicators of *Thalassinoides* in the Yeoman Formation:

Although no single criteria in itself could be used to distinguish diagenetic haloes from burrows, a combination of criteria can favour one interpretation over another. In intervals where many of the following criteria are met, mottles are interpreted as *Thalassinoides*:

- Dolomite mottles contain within the intraclasts made of the same material as the matrix, some of these appear to be collapse structures. This is probably the best evidence that the now mottles, once were open burrows. These are unfortunately rare. Note that the walls of these mottles are not sharp (Figure 2.6a).
- Contrast in fabric, allochem abundance and types, and abundance of organic matter between mottle and matrix sediment. Since the dolomitization which formed the mottling is generally fabric destructive, and increased abundance or variety of allochems within the burrow is in itself valid criteria to call the structure a burrow; however, the inverse cannot be claimed with such certainty (Figure 2.6b).
- Absence of causative burrow from mottles over an interval. Absence is only certain when the burrow is seen in cross-section. An oblique section may miss the causative burrow. One may argue it was

obliterated by the dolomitization, which formed the diagenetic mottle; however, perhaps this is an overly simple argument, since this dolomitization did not destroy the causative burrows elsewhere, it is easier to assume that they never existed

- The mottle wall is cut by burrows; i.e., the mottles do not strictly follow or completely contain smaller burrows. Or the mottle wall cross-cuts another burrow (Figure 2.7a)
- Mottles generally have sharp walls; however this criterion is not always the best see discussion below.
- Large mottles and small *Planolites* exhibit the same diagenetic fabrics and the walls of both have the same "sharpness".
- Mottles exhibit Y- and T-branching, characteristic of *Thalassinoides* (Figure 2.7b).
- Mottle diameter appears constant along the burrow axis throughout an interval.
- Mottles exhibit mechanical compaction: "broken", squashed or flattened mottles. Mechanical compaction of mottles suggests that the mottles were formed prior to sediment lithification.
- Re-burrowed by *Planolites*. The re-burrowing of large burrows is common by deposit feeders, especially where the fill of the large burrow may provide a better food source for the later burrows (Bromley, 1996).
- Occur in intervals that contain firmgrounds with *Thalassinoides*. This is merely circumstantial evidence; if such organisms existed, which were large enough to create *Thalassinoides* at the firmground intervals, would they not exist before and after?

One of the criteria noted by Bromley (1996) and cited by Gingras (2000) to determine if a structure or not is a regular, sharply demarcated boundary. A sharp wall is found not to be evidence enough for differentiating between a diagenetic fabric and biogenic sedimentary structures, because often many indisputable *Planolites* have walls, which are not sharp. Dolomitization has appeared to obscure those walls also. Dolomitization process can 'blur' the wall of a *Planolites*, it should be able to obscure the wall of a *Thalassinoides*. Furthermore, some of the mottles, which are found to contain intraclasts did not have sharp walls either. Lack of burrow wall sharpness may also result from factors other than diagenetic blurring. If the biogenic sedimentary structures were formed in a soupy or soft substrate, and there is little evidence to suggest that the precursor was a coarser grain texture, mechanical compaction of the mottles can 'blur' the walls of large *Planolites* or *Thalassinoides*. Added evidence in these intervals indicating that these mottles formed before sediment lithification are the presence of molds after halite hoppers. In order for these to form, they must have grown in a void space or in soft sediment where they can displace sediment to make room to grow. These hopper crystals, now infilled with saddle dolomite, less commonly anhydrite, are found more commonly, but not exclusively in the dolomite mottles, which fit the other criteria for *Thalassinoides*.

Collective Indicators of Diagenetic Haloes:

The following criteria, when found together within an interval, are here taken to collectively favour a diagenetic halo interpretation:

- No crosscutting observed between smaller burrows and the dolomite mottles over the interval.
- Outer boundary of the halo is gradational. Contrast between mottle and matrix is gradational in petrography, abundance of allochems and organic matter (Figure 2.7c).
- Dolomitization of the halo appears fabric destructive, allochems are faintly preserved, or gradually decrease in abundance towards the causative burrow.
- Diagenetic front of the dolomite halo terminates against a macrofossil, but continues further from the causative burrow in other directions.
- *Palaeophycus*, which are not eccentrically located within a dolomite mottle, suggest it is a causative burrow with a diagenetic halo.
- Mottles do not exhibit much mechanical compaction, no squashed mottles over an interval.

Locally the distinction between *Thalassinoides* and diagenetic haloes remains uncertain, especially in intervals, which are intensively affected by diagenesis. In nodular zones and stylo-mottled zones, the three-dimensional configuration is impossible to determine. Stylolites have further obliterated the nature of the mottle walls. The origin of many nodular and rubbly limestones and dolomites has been attributed to burrowing (Fürsich, 1972); therefore, these too may have been large burrow systems, but now are impossible to distinguish.

Discussion:

Those burrows identifiable as *Thalassinoides* with the greatest certainty generally occur in the same carbonate intervals that contain the kukersites. *Thalassinoides* are common at the firmground contacts between carbonate and super-adjacent kukersite, and many are re-burrowed by *Planolites*. Some examples of *Thalassinoides* are found in other Yeoman intervals. The *Thalassinoides* most likely represents the fodinichnia and domichnia of arthropods or large worms. Phyllopods were suggested by Bottjer et al. (1984). *Thalassinoides* are generally interpreted as dwelling or combined feeding-dwelling burrows. The common behavioural interpretation generally applied to the *Thalassinoides* behaviour can not be applied because the arthropods (ex. shrimps), responsible for making *Thalassinoides*, had not yet evolved in the Ordovician. Until a possible trace producer is discovered, the lower Paleozoic *Thalassinoides* may remain an enigma as stated by Myrow (1995). No organism has been observed in any of these burrows, and until such an example is found the trace maker cannot be identified with certainty. Such an example may never be found if the trace was produced by a soft bodied organism with very low preservation potential. It must be noted that the lower Paleozoic dolomite mottling, with the diffuse dolomite walls, may have been burrows formed in thixotropic sediment. Although the walls of these dolomite mottles resemble diagenetic fronts, they also fit criteria listed by Rhoads (1970) of burrows formed in a soupy (thixotropic) substrate. It may be possible that some unknown animal from the lower Paleozoic mined the sediment prior to any

dewatering and lithification, and the fill of these burrows was more susceptible to dolomitization. Their walls remained blurry due to lack of substrate consistency.

2.6 *CHONDRITES* STERNBERG, 1833

Description of Ichnogenus *Chondrites* Sternberg, 1833:

Burrows are found in vertical and horizontal section (Figure 2.8). Branches are subvertical to horizontal; however, some zones are dominated by horizontal burrows. Locally the branching is dendritic, but generally the orders and nature of branching are indeterminable. Cross-sections are elliptical to circular. These *Chondrites* are smooth-walled burrows. Sizes range from less 1 millimeter to 3 millimeters in diameter. The internal sediment is homogeneous. Fill generally contrasts by paucity of organic matter/kerogen. Locally, *Chondrites* have fill richer in organic matter/kerogen. These burrows range from good to poor preservation.

Discussion:

Chondrites are common in the muddier, organic-rich substrates, or as secondary burrows of *Thalassinoides* and composite burrows systems. They are also common in the organic-rich kukersites. *Chondrites* may occur exclusively with *Planolites*, or as part of a composite burrow system. They are generally interpreted as fodinichnia, but despite their common occurrence in sediments throughout the Phanerozoic, the trace maker has not yet been identified. The vertical upper portion, suggested by Kotake (1991) to be a domichnia, is not observed. *Chondrites* indicate a lack of oxygenation of the substrate only when occurring as a monospecific suite (Bromley and Ekdale, 1984). However, since they commonly occur as the deepest tier of trace fossils (Bromley and Ekdale, 1986) they may appear to have occurred as a monospecific suite because the high density of *Chondrites* has obliterated all other burrows. *Chondrites* are found occurring alone in some kukersites, but not in all of them (Chapter 3). They may have colonized the substrate after the deposition of the kukersite, therefore they do not necessarily indicate a low oxygen environment for kukersite deposition.

2.7 *TRICHOPHYCUS* MILLER AND DYER, 1878

Description of Ichnogenus *Trichophycus* Miller and Dyer, 1878:

Burrows are found in subhorizontal to horizontal section (Figure 2.9). *Trichophycus* are generally straight burrows, circular to elliptical in cross-section, and locally have a variable diameter along burrow axis. Burrow diameter ranges from 1 to several centimeters. One observed chamber had a diameter as great as 10 centimeters. There is little evidence of branching. Walls are irregular, locally containing ridges or grooves, which suggest scratch-marks. Stylolites and bitumen concentrated at burrow walls gives the impression of thin organic-rich lining. Burrow fill is homogeneous, but commonly contains secondary

Planolites and *Chondrites*, whose fill has a lower organic content than the *Trichophycus*. The fill of *Trichophycus* is distinctly different from the host rock. It is usually dolomitized and has a higher organic content than the matrix. Allochems are better preserved and occur in greater variety than the host sediment. The fill is richer in bryozoans, trilobites and ostracods. Excellent burrow preservation is due to lithologic contrast and high organic content of the fill.

Discussion:

The contrast between *Trichophycus* fill and the host matrix may be due to better preservation in the sheltered burrow environment. Or, the burrow fills may represent concealed bed junctions, with the burrow fill representing remnants of an eroded bed. *Trichophycus* were interpreted by Seilacher and Crimes (1969) as the feeding burrows of small trilobites. Trilobites, large enough to build *Trichophycus* of the size observed in core, are not observed in Yeoman sediments. These burrows are being distinguished from *Thalassinoides*, because there is no evidence for branching. Furthermore, their sharp walls and distinctive nature suggest a different origin than Yeoman Formation *Thalassinoides*.

2.8 *SKOLITHOS* HALDEMAN, 1840

Description of Ichnogenus *Skolithos* Haldeman, 1840:

Burrows are preserved instrastratally. *Skolithos* diameter ranges between 1 and 3 millimeters. These burrows are found to be vertical or subvertical (Figure 2.10a). Locally these burrows are curved, but generally they are straight. Burrow length is several cm, but absolute length can not be ascertained. Two types of *Skolithos* are observed. The first are lined by allochems and are only visible on freshly slabbed surfaces. The second type are more common and generally more visible, due to organic matter in their fills and linings. Burrow fill is found to be the same as the host sediment, except for those lined with organic matter are more commonly dolomitized.

Discussion:

The presence of *Skolithos* indicates enough water agitation on a regular basis for filter feeding organisms to colonize the substrate. They are rare and are commonly found in association with *Palaeophycus*. Generally, these are thought to be the vertical dwelling tubes of polychaetes; however, vertical tube components of many other trace fossils may be mistaken for *Skolithos* in core analysis.

2.9 *RHIZOCORALLIUM* ZENKER, 1836

Description of Ichnogenus *Rhizocorallium* Zenker, 1836:

Burrows are preserved intrastratally. *Rhizocorallium* occur vertically to horizontally, in random orientations throughout given intervals (Figure 2.10b, 3.8b). These U-shaped burrows show no evidence of

branching, except where they are associated with the composite burrow systems. Their thick organic-rich lining exhibits spreiten. The internal sediment of the latest burrow is generally carbonate with low organic content. *Rhizocorallium* may contain secondary *Planolites* or *Chondrites*. Burrow diameter ranges from 1 to 5 millimeters, with the lining thickness ranging from 5 μm to few millimeters. The burrow length is indeterminable. Fill may contrast in both mineralogy and organic content from the host matrix. Generally lining of these burrows has much greater organic content than the host sediment. If the organic matter is not degraded, it is dominantly disseminated A and B *G. prisca* alginite. *Rhizocorallium* are also observed in kukersitic intervals (Figure 4.11a), where fill is depleted in organic matter. Burrow density is variable, but these sediments are never fully bioturbated by *Rhizocorallium*.

Discussion:

Rhizocorallium have been interpreted to represent both suspension- and deposit-feeding activities. Since the large three-dimensional aspect of the burrow cannot be determined in core, there is not enough evidence to determine the criteria Fürsich (1974a) used to distinguish the two. The larger 3-dimensional configuration of this burrow is used to make this distinction. *R. jenense*, representing more or less straight, short, and commonly oblique spreiten burrows are interpreted as the dwelling burrows of filter feeders (Fürsich, 1974a). The abundance of *G. prisca* in burrow linings, combined with its absence in burrow fills and host matrix, suggests that the organisms incorporated these maceral varieties into the burrow lining. This further suggests that *Rhizocorallium* were produced by filter-feeding or surface detritus feeding behaviour.

2.10 *ASTEROSOMA* VON OTTO, 1854

Description of Ichnogenus *Asterosoma* von Otto, 1854:

Asterosoma-like structures are found in both horizontal cut as well as vertical section, preserved intrastratally (Figure 2.11). These also are commonly associated with the composite burrow systems. Their orientation is horizontal to subhorizontal, no related vertical shafts are observed. They are curved, bulbous burrows with lobes. No evidence of branching is found. Walls are annulated, containing several concentric layers of organic matter. The internal fill usually consists of low organic content carbonate sediment, sometimes with meniscate structures. Carbonate fill commonly is dolomitized, as is the carbonate component of the burrow lining. Burrow diameter in cross-section ranges from 1 to 6 millimeters. If the organic matter is not degraded, it is dominantly disseminated A and B *G. prisca* alginite. Thickness is variable along length, which in turn is often indeterminable, due to curvature of lobe. Preservation of lobes is good, due to enhanced recognizability by organic lining, but the vertical shafts are not observed with any confidence.

Discussion:

Evidence of multiple bulbs is limited to 2 in horizontal section, however vertical sections are indicative of *Asterosoma*-type behaviour. Generally these are part of the composite burrow systems, which also exhibit other similar feeding behaviours. Farrow (1966) found *Asterosoma* occurred in finer, more argillaceous sediments deposited further from the shoreline. Although, he inferred they may have been of either crustacean or annelid origin, today, *Asterosoma* are believed to be the feeding (fodinichnia) structures of worms. The organism is believed to have probed repeatedly into the sediment to enlarge the gallery and work more and more sediment vertically and laterally (Chamberlain, 1971). *Asterosoma* found in kukersites are believed to have formed by this mechanism; however, *Asterosoma*-like components of the composite burrow systems (where they are not secondary burrows having exploited the linings of earlier burrows) are believed to have resulted from waste-stowage type behaviours like those described by Kotake (1991) and Bromley (1991).

2.11 *TRYPANITES* MÄGDEFRAU, 1932

Description of Ichnogenus *Trypanites* Mägdefrau, 1932:

Borings are preserved between stratal contacts (Figure 2.12). Visible as 'piped' zones, introducing sediment from overlying layer into underlying layer. Most commonly at the base of kukersitic intervals, however they have been observed at the upper surface of a kukersite or between two adjacent carbonate layers. Their fill therefore contrasts to that of the host rock. Those lying between kukersite and carbonate sediment are the most easily recognized. These borings have vertical openings and may remain vertical, or curve to a horizontal chamber. *Trypanites* are rarely branched, commonly have a lobate or bulbous shape. Boring diameter generally changes if it is branched. Walls are generally sharp and appear to be smooth. The internal sediment is homogeneous, except for common secondary burrows, of ichnogenus *Asterosoma*, *Planolites*, or *Chondrites*. The secondary burrows are evident from a contrastingly lower organic content in their fill. Boring diameters can range from a couple of millimeters to > 1 centimeter. The length ranges from 1 centimeter to an indeterminable length. Preservation is excellent, except where stylolites have formed along the hardground and have destroyed the contact. Commonly in these occurrences a hardground is inferred from the presence of borings in the carbonate sediment underlying the stylolitic contact.

Discussion:

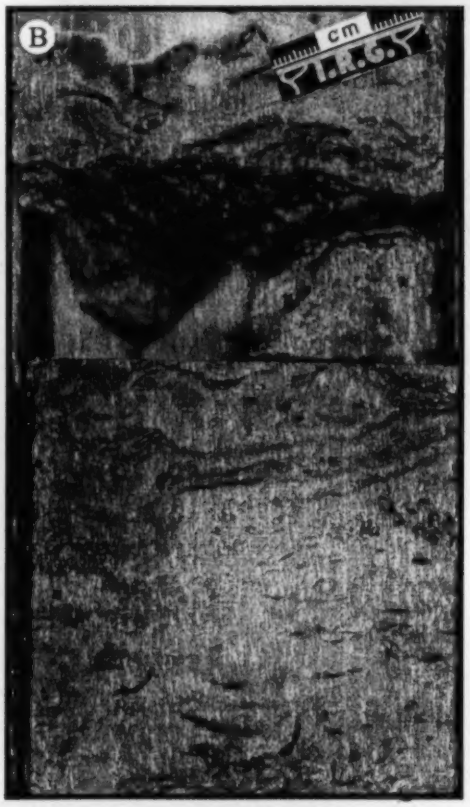
Most commonly *Trypanites* occur below facies 4, kukersite zones, however they have been observed between adjacent carbonate beds. Contacts are commonly destroyed by pressure solution. Former existence inferred from boring found below a thick stylolite, rich in organic matter and kerogen. Thin sections are commonly required to differentiate from *Thalassinoides* at a firmground, and commonly there is no evidence (sutured allochems and cut fabrics) in samples to determine whether the substrate was cemented or not at the time of formation of these biogenic sedimentary structures. A possible hypothesis

for these "borings" may be as burrows at omission surfaces described by Palmer (1978). He hypothesized that sediment around burrows became lithified while the burrows remained open, and the surface subsequently became a hardground during sediment bypassing. This hypothesis, suggesting that these are pre-omission suites burrows (Bromley, 1975), may explain the presence explain the *Thalassinoides*-type burrow morphologies observed at hardgrounds. Further evidence for this hypothesis, is the absence of encrusting organisms on many of these hardground surfaces. Potentially at time of cementation, the sea-floor conditions were adverse to encrusting fauna; for example, sea-floor anoxia may have existed when the organic-rich kukersites were deposited overlying the hardgrounds.

2.12 Conclusions

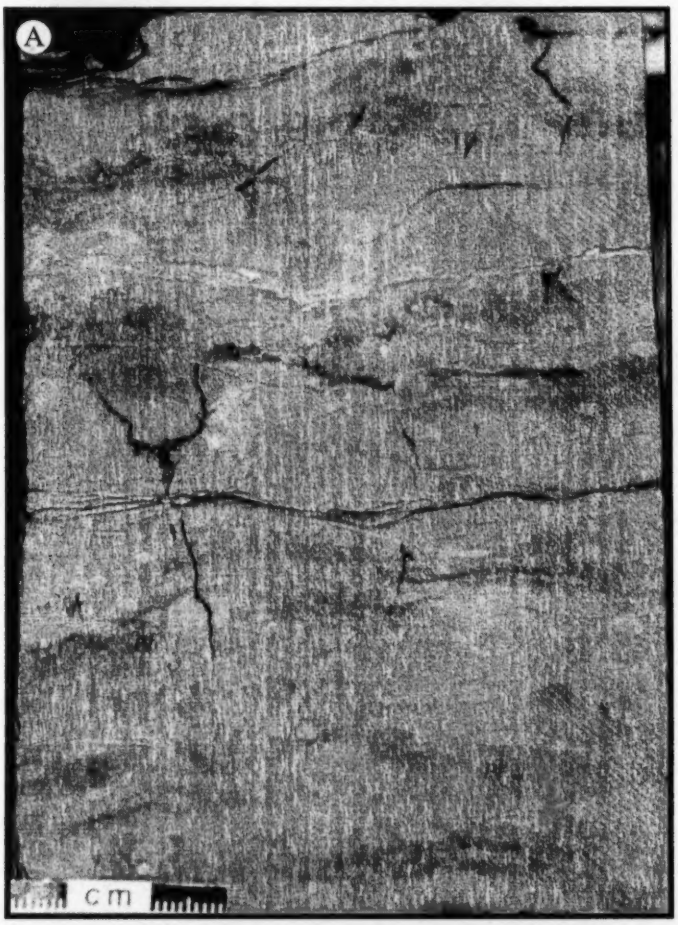
Description and classification of trace fossils in the Yeoman Formation is necessary since they are related to the most conspicuous characteristic of these sediments, namely, the dolomite mottles. Their presence has important implications on both sedimentology and diagenesis. Detailed examination of the dolomite mottles indicates that many indeed represent *Thalassinoides*, but until the trace-making organism is identified, this will remain debatable. In the examination of the biogenic sedimentary structures of the Yeoman Formation, nine discrete trace fossils are observed, many being part of composite burrow systems. Many of these burrows, except *Trypanites*, *Trichophycus* and *Palaeophycus*, are indicative of feeding activities. The diversity of forms gives the impression of a diverse benthic fauna. It is believed that the relatively uniform diameter of these feeding burrows suggests that a small group of organisms may have been responsible for the various forms. These burrowing organisms shifted their feeding behaviour in response to changes in paleoenvironemental conditions, such as water energy, depth, oxygenation, and nutrient availability. Chapter 4 explores the potential of these trace fossils as indicators of change during deposition of the Yeoman Formation. The following chapter discusses how the distribution of organic matter in these burrows may provide insight into the nature of an enigmatic algal microfossil, *Gloeocapsomorpha prisca*.

Figure 2.1 *Palaeophycus* in the Yeoman Formation



A. *Palaeophycus* in a wack/packstone matrix, facies 2. 21/8-17-13-13W2/0, 2170.8 m.
B. *Palaeophycus* with very thin dolomite haloes, facies 2. 11/9A-28-6-11W2/0, 2609.1 m.

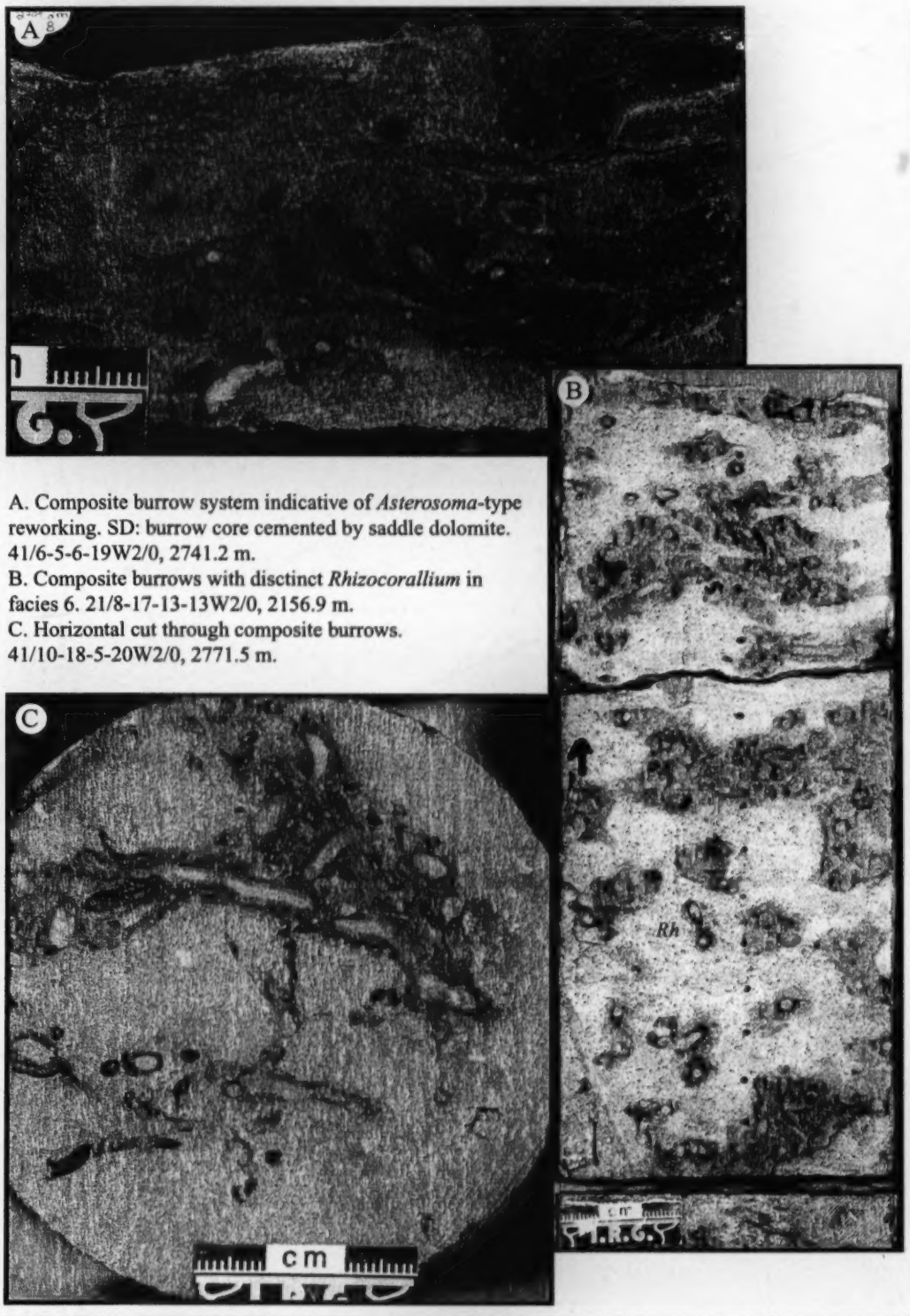
Figure 2.2 *Planolites* in the Yeoman Formation



A. *Planolites* in facies 8. Note variability in burrow diameter. 21/8-17-13-13W2/0, 2164.5 m.

B. *Planolites* with thin diagenetic haloes, in facies 8. 41/6-5-6-19W2/0, 2746.3 m.

Figure 2.3 Composite Burrows in the Yeoman Formation



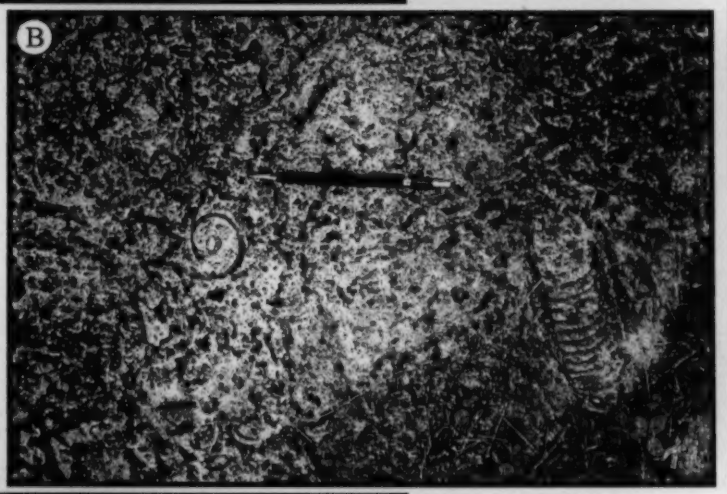
A. Composite burrow system indicative of *Asterosoma*-type reworking. SD: burrow core cemented by saddle dolomite. 41/6-5-6-19W2/0, 2741.2 m.
B. Composite burrows with disctinct *Rhizocorallium* in facies 6. 21/8-17-13-13W2/0, 2156.9 m.
C. Horizontal cut through composite burrows. 41/10-18-5-20W2/0, 2771.5 m.

Figure 2.4 Composite Burrows in the Yeoman Formation

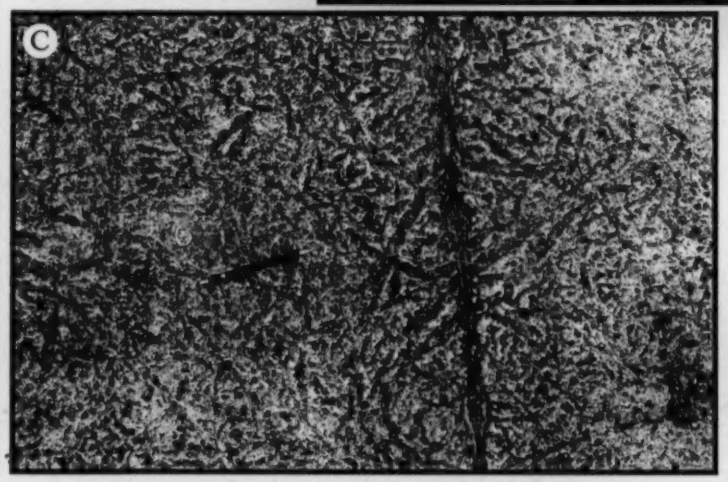
A. Composite burrows with pressure solution at burrow walls. Minimal fracture and moldic burrow porosity. 21/8-17-13-13W2/0, 2151.0 m.
B. Composite burrows with many *Palaeophycus*-like components. 41/10-18-5-20W2/0, 2771.5 m
C. Horizontal section of composite burrow. 41/10-18-5-20W2/0, 2771.9 m.

Figure 2.5 *Thalassinoides* in the Lower Yeoman Formation

A. *Thalassinoides* parallel to the bedding plane. Preferential growth of fungi suggestive of burrow patterns. Outcrop of Lower Red River Formation, near Amisk Lake, Saskatchewan. Pencil 14 cm.

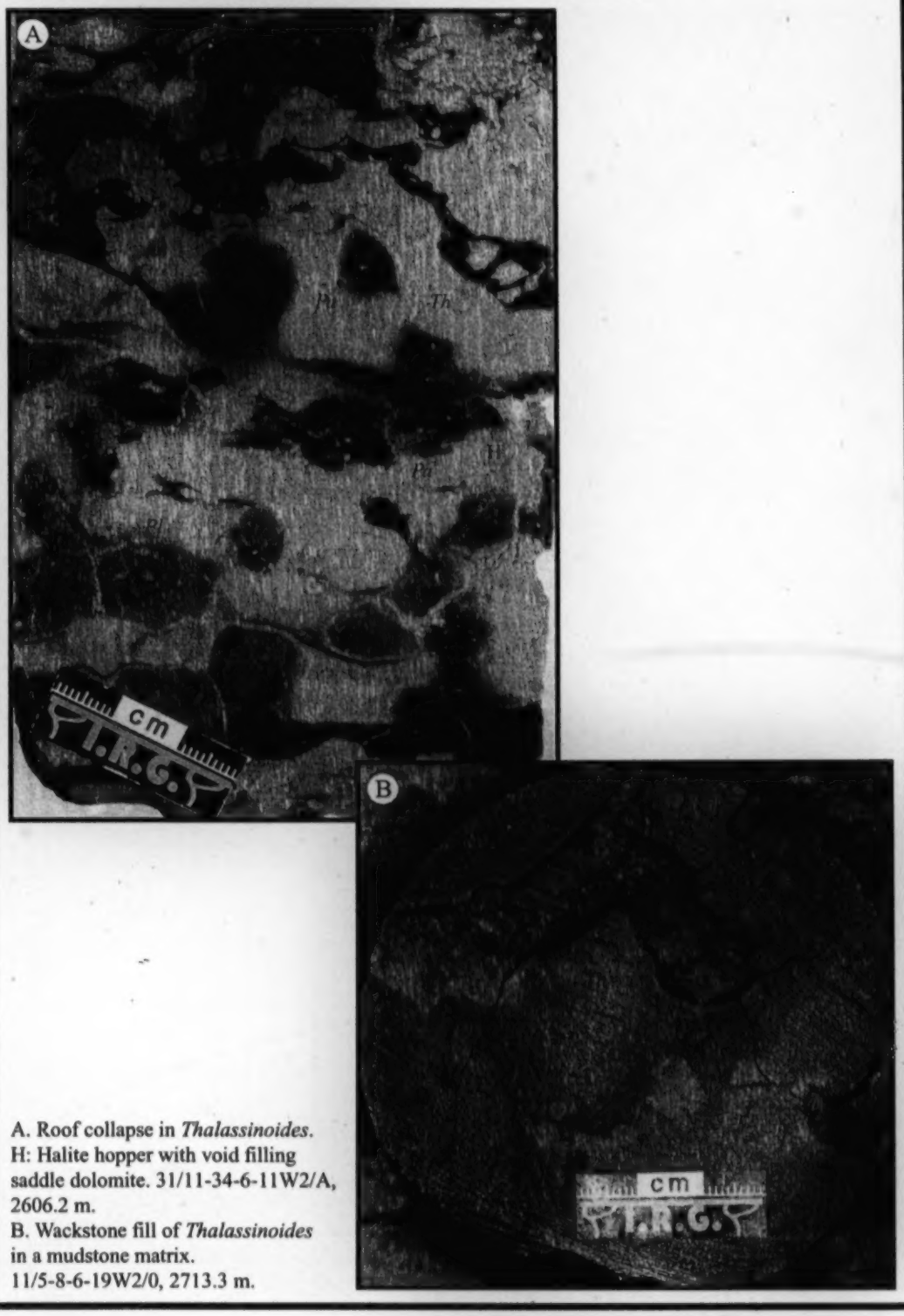


B. *Thalassinoides* parallel to the bedding plane. Preferential growth of fungi and differential weathering indicative of biogenic sedimentary structures. Note similar preservation of gastropod and cephalopod. Outcrop of Red River Formation on the western shore of Amisk Lake, Saskatchewan. Pencil 14 cm.



C. Preferential growth of fungi and differential weathering indicative of biogenic sedimentary structures. Outcrop of the Red River Formation on the western shore of Amisk Lake, Saskatchewan. Pencil 14 cm.

Figure 2.6 *Thalassinoides* in the Yeoman Formation

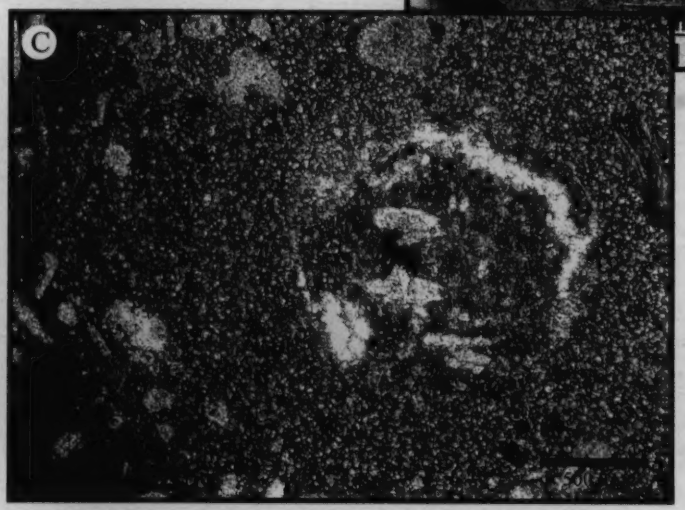


A. Roof collapse in *Thalassinoides*. H: Halite hopper with void filling saddle dolomite. 31/11-34-6-11W2/A, 2606.2 m.
B. Wackstone fill of *Thalassinoides* in a mudstone matrix. 11/5-8-6-19W2/0, 2713.3 m.

Figure 2.7 *Thalassinoides* in the Yeoman Formation

A. *Thalassinoides* reburrowed by *Palaeophycus*. Note *Palaeophycus*, which crosses the *Thalassinoides* wall. 41/10-18-5-20W2/0, 2778.6 m.

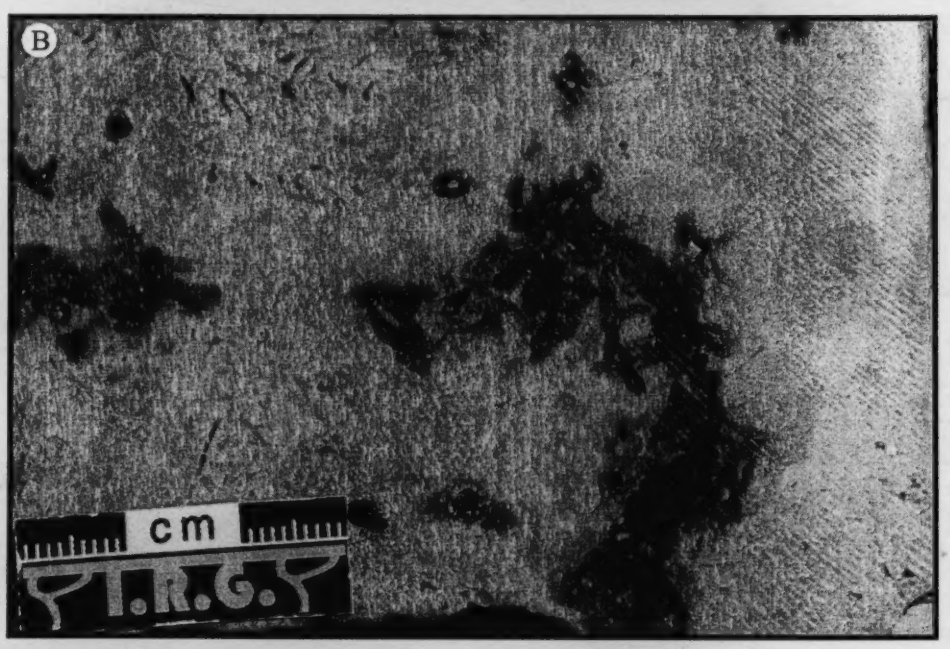
B. *Thalassinoides* exhibiting Y-Shaped branching. Reburrowed by *Planolites*. Note *Palaeophycus* in matrix without diagenetic halo. 11/5-8-6-19W2/0, 2719.2 m..



C. Diagenetic dolomite haloes commonly form around smaller burrows. Type 1 dolomite mottle, chapter 5. Polarized light. Scale bar 500 µm. 11/5-8-6-19W2/0, 2710.0 m.

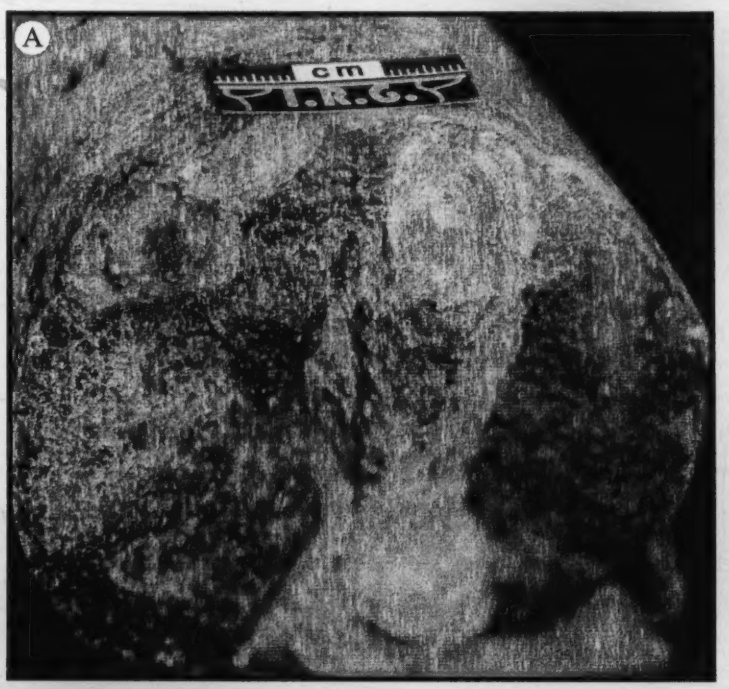
Figure 2.8 *Chondrites* in the Yeoman Formation

A. *Chondrites* in facies 8. 41/2-10-7-11W2/0, 2576.5 m.

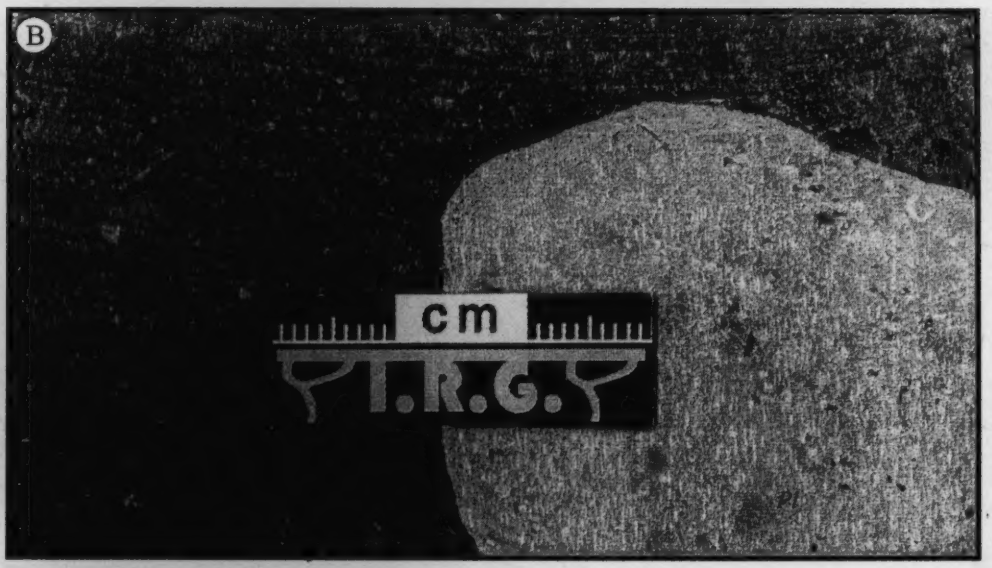


B. *Chondrites* from facies 3. 21/8-17-13-13W2/0, 2165.0 m

Figure 2.9 *Trichophycus* in the Yeoman Formation

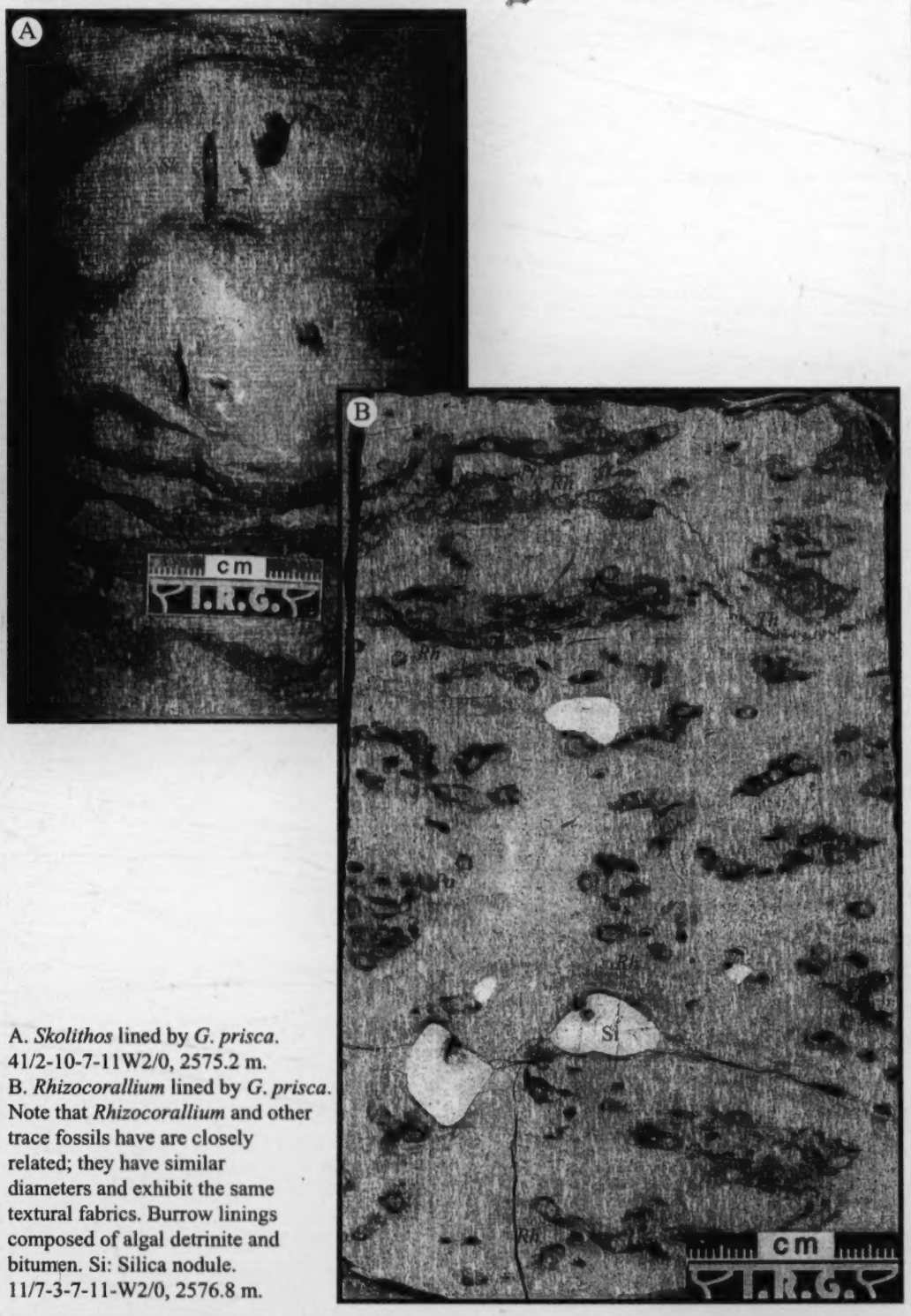


A. *Trichophycus* in horizontal section, from facies 1. 11/7-3-7-11W2/0, 2613.4 m.



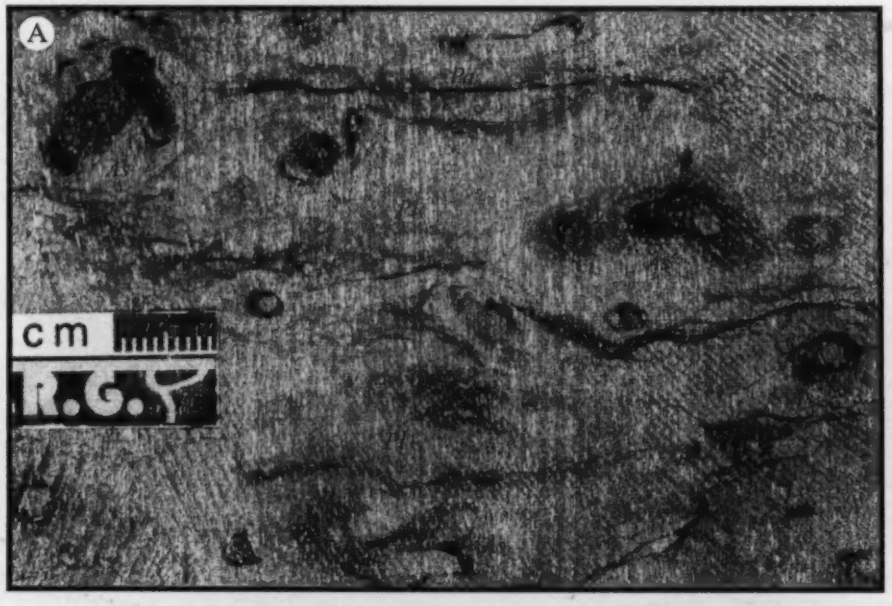
B. *Trichophycus* in vertical section, from facies 2. *Planolites* in both matrix and *Trichophycus* fill. 11/5-8-6-19W2/0, 2738.0 m.

Figure 2.10 *Skolithos* and *Rhizocorallium* in the Yeoman Formation

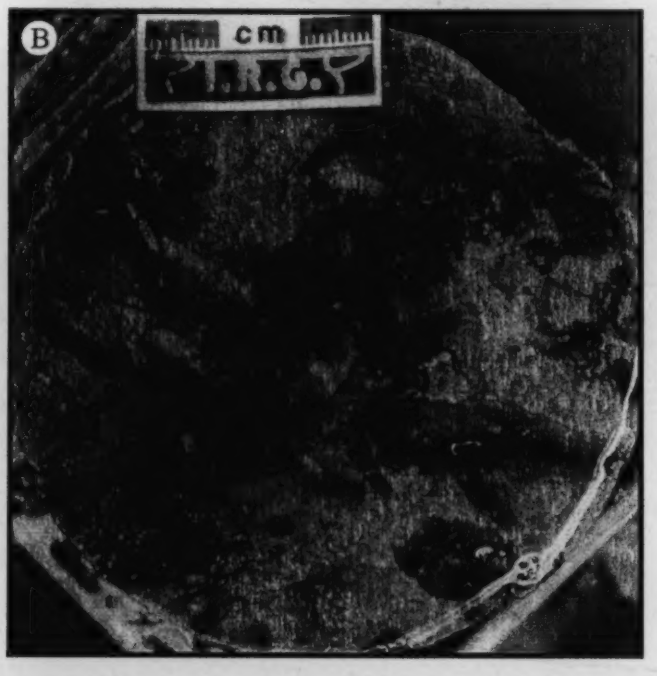


A. *Skolithos* lined by *G. prisca*. 41/2-10-7-11W2/0, 2575.2 m.
B. *Rhizocorallium* lined by *G. prisca*. Note that *Rhizocorallium* and other trace fossils have are closely related; they have similar diameters and exhibit the same textural fabrics. Burrow linings composed of algal detrinite and bitumen. Si: Silica nodule. 11/7-3-7-11-W2/0, 2576.8 m.

Figure 2.11 *Asterosoma* in the Yeoman Formation



A. *Asterosoma*, *Palaeophycus* and *Planolites* in facies 6. 21/8-17-13-13W2/0, 2157.4 m.



B. *Asterosoma*-like components of composite burrows in horizontal section. 01/8-3-7-11W2/0, 2596.0 m.

Figure 2.12 *Trypanites* in the Yeoman Formation

A. Borings at the base of a kukersite. 11/5-8-6-19W2/0, 2719.8 m.

B. *Trypanites*. 21/B6-20-6-13W2/0, 2628.6 m.

C. *Trypanites* at the base of a kukersite. 41/7-2-9-13W2/0, 2444.4 m.

CHAPTER 3. IMPLICATIONS ON THE NATURE OF KUKERSITES FROM ICHNOLOGY

3.1 INTRODUCTION

In the course of examining the trace fossils of the Yeoman Formation, close relationships were observed between the dispersed organic matter (DOM) and macerals (kerogen) and the biogenic sedimentary structures. The macerals in these sediments are dominantly composed of the algal microfossil, *Gloeocapsomorpha prisca* alginite, believed, until recently, to have lived only during the Ordovician (Fowler and Stasiuk, 1999). Kukersites, deposits with greater than 90% kerogen content by volume (~35 wt% carbon) made up of *G. prisca*, have sourced most of the oil within Red River Reservoirs in the Williston Basin (Stasiuk and Osadetz, 1991), as well as many Ordovician hydrocarbon deposits world wide (Zhmur, 1991; Summons and Powell, 1991; Reed et al., 1986). These Ordovician oils have a distinct chemical signature, including a very high concentration of n-alkanes (up to C^{19}) with a strong odd-carbon-number predominance, very low acyclic isoprenoids and polycyclic alkanes, and a relatively high concentration of monocyclic alkanes (Fowler, 1992). All of these unique characteristics are attributed to the maceral *G. prisca*.

To date, no agreement has been reached concerning the life style of this organism, and the accumulation of beds rich in *G. prisca*. The more popular view is that *G. prisca* was a non-photosynthetic, prokaryotic, benthic algal mat (Reed et al., 1986; Foster et al., 1989, 1990); others believe it was a photosynthetic, eukaryotic, planktonic organism (Hoffman et al., 1987), possibly prokaryotic (Stasiuk and Osadetz, 1990; Stasiuk et al., 1993), which bloomed episodically throughout the Ordovician. Much of the evidence for these hypotheses lies in geochemical evidence. Based on petrographic studies, Stasiuk and Osadetz (1990) found evidence that the organism passed through both a planktonic and benthic stage of its life cycle, and microtextures in the algal mat stage, which typify a photosynthetic response. It is the purpose of this chapter to describe the relationship between the organic matter (hereafter referred to as DOM/kerogen) and the biogenic sedimentary structures of the uppermost Yeoman Formation. Organic petrography is used to determine the maceral variety of the organic matter. Many trace fossils are indicative of feeding behaviours. Depending on the nature of *G. prisca*, these algal microfossils were consumed and processed differently by burrowing infauna. Based on the distribution of *G. prisca* within the trace fossils of the Yeoman Formation, a planktonic nature for this microfossil better explains the accumulation of kukersites in southeastern Saskatchewan.

3.2 Previous Studies of *Gloeocapsomorpha prisca*

Kukersites are found in widespread geographical localities (Reed et al., 1986), and reconstruction of Ordovician paleogeography shows that these deposits were geographically widespread at the time of deposition (Ziegler et al., 1979). These deposits are generally associated with epicontinental carbonates, but also occur concomitantly with organic shales. The organism lived in low latitude tropical seas (Foster et al., 1986). Accumulation must have occurred under unique conditions in which growth was optimal and/or such that they prevented the reworking of primary organic matter. This organism has not been found in any rocks undisputedly younger or older than the Ordovician, and thus is believed to have gone extinct during one of the largest mass extinctions of Phanerozoic marine life, which occurred at the Ordovician-Silurian boundary. Recent discoveries may indicate that this is incorrect, since Fowler and Stasiuk (1999) have found *bona fide G. prisca* alginite in Upper Devonian strata in southern Alberta. They believe *G. prisca* may have survived the extinction, but never thrived as it did during the Ordovician.

Gloeocapsomorpha prisca was named and first described by Zalessky (1917). He offered two scenarios for explaining the origin of *G. prisca* accumulation in sediments. His first hypothesis was that *G. prisca* was a planktonic organism that bloomed on the surface of saline lakes, subsequently sank and thus was incorporated authochthonously into bottom sediments. The second allochthonous hypothesis was that *G. prisca* was a benthic organism, coating shoreface rocks. Offshore accumulation and deposition was caused by storm transportation (Foster et al., 1990). Most subsequent studies have taken one of these two views, the benthic algal mat being the more popular. Although there are few contradictions in the observations, the interpretations, which rely largely on geochemical studies, are conflicting.

Reed et al. (1986) examined core samples from the Trenton Formation (Michigan and Illinois Basins), Viola Formation (Oklahoma Basin) and Red River Formation (Southern Williston Basin). In all of their samples *G. prisca* occurs as thin, undisturbed organic rich laminae contained within thicker sections of bioturbated calcareous sediment. Deposition in shallow, oxygen-rich water suggests that *G. prisca* was not a free-floating organism, but formed in benthic, mat-like communities. They reasoned that since mat-forming communities commonly have localized anoxic conditions, the preservation of mat-like communities in an otherwise oxygen-rich environment could be explained.

Foster et al. (1989, 1990) came to similar conclusions examining the Baltic shale, in Estonia. They suggested the extant *Entophysalis major* as a modern analogue for *G. prisca*. They believed *G. prisca* was a similar colonial organism that was an intertidal, marine, mat-forming benthic cyanobacterium, which may form stromatolites. Kukersite beds are formed in situ or occur as allochthonous deposits resulting from transport of *G. prisca* from large intertidal areas by water or wind current into anoxic offshore environments. It was proposed that the cyclical nature of sediments containing kukersite and marine carbonate facies in the Baltic Shale Basin result from changes in relative sea level, probably caused by both local tectonism and eustatic sea level changes. In their 1990 paper, they suggested a condensed section interpretation for the kukersite beds, especially the thick ones.

After performing extensive geochemical analyses of organic-rich sediments from the Canning and Amadeus Basins of Australia, Hoffman et al. (1987) came to different conclusions about *G. prisca*. Evidence from the pyrolysis of fossil cells of *G. prisca* indicate that it was a lipid rich organism, with abundant fatty acids and steroids and a chlorophyll containing phytol. Together with light ^{13}C values, these factors argue that *G. prisca* was probably planktonic and a phototroph, possibly a eukaryotic alga, widely distributed in marine environments during the Ordovician. From a detailed geochemical analysis of the Decorah Formation of eastern Iowa, Ludvigson et al. (1996) determined that *Gloeocapsomorpha prisca* could not have inhabited the benthic environment and thus must have been a phytoplanktic organism.

Based on a study examining the organic petrography of Williston Basin kukersites, Stasiuk and Osadetz (1990) expanded the debate. They concluded that the hypotheses of both Reed et al. (1986) and Hoffman et al. (1987) were partially correct. Evidence exists to suggest that *G. prisca* had a life cycle, which included both planktonic, and benthic life stages. Depending on the stage of its life cycle it could be either. The two maceral varieties corresponding to the planktonic stage were called disseminated A and B (Table 3.1). Fowler (1992) concluded that, based on current information, it could not be determined whether *G. prisca* was eukaryotic or prokaryotic. By comparison with other Ordovician organic rich rocks, he deduced that no evidence existed to suggest *G. prisca* was deposited under hypersaline conditions.

Table 3.1 Classification used in this study for dispersed organic matter constituents or macerals.

Maceral	Submaceral	Maceral Variety	Criteria
Alginite	*G. prisca*	Disseminated A	2-15 μm, thin-walled, ~ 2 to 15 cells
		Disseminated B	> 15 μm, thicker-walled, > 15 to 100's cells
		Stromatolitic	layered with upper surface algal mat microtextures
	Leiosphaeridiai		thin-walled
	Tasmanites		thicker-walled; punctuate margin
Acritarchs	Acanthomorphic		5-50 μm, spiny
	Sphaeromorphic		5-50 μm, no spines
Algal detrinite			< 5-10 μm, broken, alginite-like
Acridetrinite			< 5-10 μm, broken acritarch-like
Amorphinite			non-descript amorphous fluorescing DOM
Zooclasts	Chitinozoan		
	Scolecodonts		
Bitumen			oily, infilling pore space, dark to brown to orange fluorescing

Table courtesy of L.D. Stasiuk.

3.3 Observations on Kukersites in the Yeoman Formation

Kukersites are found in the uppermost ¼ of the Yeoman Formation in all of the examined oil pools. Sedimentary fabrics are better preserved in cores from the Tyvan pool where pressure solution and dolomitization were not as severe. Lower maturation of kukersites (yellow brown to red rather than black in core), which have not reached the oil window, contain better-preserved sedimentary structures compared with those of higher maturity. Based on fluorescence properties and morphology, the DOM/macerals are less degraded at Tyvan than those at the Midale and Ceylon pools. Less bitumen in the Tyvan pool cores also allows the maceral variety of *G. prisca* to be better examined. Within a single oil pool, commonly kukersites can be correlated (Figure 3.1), and this is consistent with the observations of Kent and Haidl (1999), who found that two of the kukersites could be correlated throughout southeastern Saskatchewan. Most of the examined cores contain 7 kukersites, and the greatest number of organic-rich beds are observed at Tri Link Tyvan 21/8-17-13-13W2/0.

Kukersites occur in thin laminae or beds up to 20 centimeters thick, if they have not been obliterated by pressure solution (Figure 3.2, 4.11a,b). Fossil and trace fossil assemblages are commonly well preserved. Fossil debris found in the organic-rich carbonates consist of fully open marine fossils, such as trilobites, crinoids, brachiopods and rugose corals. These beds contain the disseminated B maceral variety of *G. prisca* alginite (*sensu* Stasiuk and Osadetz, 1990) or algal detrinite, presumably derived also from *G. prisca*.

The carbonates, below the lowermost kukersite, contain *Planolites*, *Palaeophycus* and *Chondrites*. There is a gradual increase in the thickness of the organic lining of *Palaeophycus* upward (Figure 3.3). *Chondrites* directly below the contact are filled with DOM/kerogen, as are the *Trypanites*. There is an absence of DOM/macerals, particularly *G. prisca* alginite, in the matrix and *Planolites*, which represent deposit-feeding activity.

The pattern of increasing organic matter in burrow linings up towards the base of kukersites is observed in the subsequent carbonate-kukersite cycles. In the uppermost tens of centimeters of carbonate sediment below the base of a kukersite, there is a gradational change from lined burrows to burrows fully filled with organic-rich sediments (Figure 3.4). Where not destroyed by pressure solution, the lower contact of kukersite beds commonly is a sharp surface. It must be noted, that in some places the hardground contact is missing from the core, but it can be inferred because borings filled, with kukersitic material, are found in the core piece below. This surface is a firmground burrowed by *Thalassinoides* (Figure 3.5a) or more-commonly a hardground bored by *Trypanites* (Figure 3.5b). The diameter of these borings and burrows can range from a few millimeters to few centimeters, with those larger specimens likely being *Thalassinoides*, which formed prior to cementation of the substrate. These borings and burrows also contain the same skeletal debris as the overlying kukersite interval, and their fill is commonly re-burrowed by *Planolites*, *Asterosoma* or *Rhizocorallium* (Figure 3.5). The fill of the secondary burrows is depleted in organic matter, indicating that these burrows represent deposit-feeding activity (Figure 3.6b, 4.11a).

The organic matter in the fill of these burrows and borings directly below the kukersites is dominated by *G. prisca* disseminated B alginite and algal detrinite of probable *G. prisca* origin (Figure 3.6a). These uppermost 10-20 centimeters below kukersites greatly resemble 'piped zones' described in the rhythmically bedded Upper Cretaceous Demopolis Chalk (Locklair and Savrda, 1998), and similarly the kukersite filled burrows and borings represent a later tier of burrows than *Planolites* found in the matrix. The organic matter in the kukersite beds is also composed of disseminated B *G. prisca* and algal detrinite suggestive of this larger maceral variety of *G. prisca*. Confirming that the algal detrinite was sourced from *G. prisca* is possible by confocal laser scanning microscopy or pyrolysis-gas chromatography and biomarker analysis, but such detailed analysis is beyond the scope of this study.

The upper contact of kukersites is usually gradational, although locally it appears sharp, representing probable hardgrounds. Some kukersites contain a lower proportion of disseminated organic matter and these typically have both gradational bottoms and tops. Burrows found within the kukersite beds are generally dominated by *Planolites* (Figure 3.7a) and *Chondrites* (Figure 3.7b), but locally contain *Asterosoma* and *Rhizocorallium* (Figure 4.11a). Their expression is variable in size and shape. Locally, spreite are observed in them. Some contain well-developed *Chondrites*, while others are thoroughly bioturbated and exhibit few identifiable traces. Their fill is generally devoid of organic matter, suggesting that deposit-feeders were consuming the *G. prisca* (Figure 3.6b).

In the non-kukersitic intervals, organic matter is found lining *Asterosoma*, *Rhizocorallium*, *Skolithos*, *Palaeophycus* and the composite burrows (Figure 3.8, 2.3, 2.4). As the amount of DOM/kerogen increases upward to the base of the kukersites, so does the proportion of *G. prisca* relative to other types of macerals (spiny, acanthomorphic acritarchs, Leiosphaeridiai) and zooclasts (chitinizoans and scolecodonts). These are best preserved in samples examined from Tyvan. Amorphous organic matter, algal detrinite and bitumen are more abundant in Ceylon and Midale. The thickness of burrow linings varies from < 1 millimeter to several millimeters. In facies dominated by *Palaeophycus* and *Skolithos*, burrows generally have thin organic linings composed of acritarchs, disseminated A *G. prisca* and algal detrinite (Figure 3.9a,b). The size (~10 μm) and fluorescence color emission (low intensity brown to red brown) of the algal detrinite is suggestive of the smaller disseminated A *G. prisca* alginite; although confocal laser scanning microscopy or pyrolysis-gas chromatography and biomarker analysis could unequivocally confirm this.

As the burrow linings become thicker upward, the variety of *G. prisca* maceral also shifts from disseminated A to disseminated B. *Asterosoma* and *Rhizocorallium*, with thicker reworked linings, commonly also containing disseminated B *G. prisca* alginite (Figure 3.10). Other varieties of DOM/organic matter/kerogen are rare in those burrows. Where organic matter is degraded, it occurs in larger aggregates (> 15 μm) suggestive of the disseminated B *G. prisca* maceral variety. The fill of secondary *Planolites* and the latest burrow in the composite burrow systems is devoid of kerogen/DOM/organic matter. These organic-lined burrows occur in packstones, wackstones and mudstones, suggesting that neither the activity of the producing organism, nor the presence of *G. prisca*, was restricted to a single type of substrate. Unlined burrows, *Planolites*, are commonly seen in the carbonate matrix, concomitant with the lined

burrows (Figure 3.8b). A major difficulty with identifying *Planolites* is that they are typically visible only on a freshly-slabbed surface.

3.4 Discussion

Many benthic organisms feed on dissolved or particulate organic matter in the water column and detritus at the sea floor (Schäfer, 1972). Depending on whether *G. prisca* grew as an algal mat or stromatolite on the seafloor, or accumulated from planktonic algal blooms in the water column, they would have been consumed and processed differently by burrowing infauna. This is especially apparent when comparing how organic matter is distributed in suspension and various types of deposit-feeding burrows. The incorporation of DOM/kerogen into borings and burrows outside the kukersite-rich beds must also be accounted for. Burrows within the kukersite beds can provide some clues.

Benthic organisms, which feed on organic detritus, can be subdivided into five trophic groups (Turpaeva, 1957 *in* Walker, 1972). For the purposes of this study, the distinction between the following three is necessary: swallowers, collectors and filterers. Distinction between their filterers-A and filterers-B is not necessary or possible in this study; furthermore, it is likely that most infaunal suspension feeders belong to their low-level suspension feeding group (filterers-A), i.e they filter food from near the sediment water interface. Swallowers, or infaunal deposit-feeders ingest sediment and dissolve organic matter from among sedimentary grains (Bromley, 1996). Collectors are epifaunal or infaunal deposit-feeders, which scavenge and browse the sea floor for nutrients. Many sea-floor detritus-feeding organisms stow their waste below the sediment water interface (Kotake, 1991; Bromley, 1991), as do some filter-feeders. Traces recording these three feeding behaviours are observed in the Yeoman Formation.

Intertidal Algal Mat Model

If one assumes the more popular view that *G. prisca* grew as a benthic, algal mat (Foster et al., 1989a, 1989b, 1990; Reed et al., 1986; Zhmur, 1991; Stasiuk and Osadetz, 1990; Stasiuk et al., 1993), then the depositional history of kukersite beds and the adjacent carbonate sediments of the Yeoman Formation would be described in the following manner.

Normal to minimally restricted carbonate deposition takes place, as is considered typical of most Ordovician epeiric seaways (Zenger and Lemone, 1995). The normal marine fossil assemblages in beds both above and below the kukersites suggest this (Fürsich, 1994). These normal conditions were periodically interrupted manifesting changes in any or all of the following: sedimentation rate, nutrient availability, water salinity, circulation, depth or oxygenation, which transformed depositional conditions into a more restricted setting. These new conditions would likely have provided for optimal growth and development of *Gloeocapsomorpha prisca* algal mats (Figure 3.11a).

Kukersite comprised of such algal mats would contain a fauna of their own, presumably dominated by soft bodied organisms based on the prominent *Rhizocorallium*, *Chondrites* and *Planolites* found within *G. prisca* rich sediment. Hard-bodied fossils, such as rugose corals and trilobite remains, are

commonly better preserved within kukersites than in adjacent carbonate sediment. Algal mat (stromatolitic mat) growth then flourishes until conditions return to ambient, normal marine. These events occur cyclically, as indicated by the repeated pattern in successive beds.

If the *G. prisca* deposits represent in situ, intertidal algal mats, one would have to presume a sufficient decrease in water depth to transfer the areal extent of the given kukersite into the intertidal range. Some kukersite beds are correlatable over much of southeastern Saskatchewan (Kent and Haidl, 1999); however, it is unlikely that such a large area could then have been in the intertidal range at one time. Although Foster (1989a, 1990) quoted evidence for subaerial exposure in sediments of the same age as the Estonian kukersites in Scandinavia, to the knowledge of this author, none have been recorded in any other kukersite-rich deposits. No evidence of subaerial exposure has yet been found in the Yeoman Formation cores by this or any other investigator. Fossil debris found in the organic-rich carbonates consist of fully open marine fossils, such as trilobites, crinoids, brachiopods, and rugose corals. While one could invoke transport of these fossils into the intertidal, this does not account for their excellent preservation, with low fragmentation. Subaerial exposure would have exposed them to severe diagenetic conditions, especially leaching. Therefore, unless the sedimentation rate was extremely rapid, it is unlikely they would be so well preserved. The more diluted kukersite intervals could not be considered in situ, because they contain abundant fossils, with no evidence of subaerial exposure; i.e. there is no evidence of meteoric diagenesis in any Yeoman sediments. Furthermore, it is generally agreed upon that the Yeoman Formation (Red River 'C' Burrowed Member) was deposited subtidally (Kendall, 1976; Kent and Haidl, 1999).

Subtidal Algal Mat Model

Based on the preceding, if the kukersites were deposited in situ, a subtidal algal mat interpretation must be invoked. The only other alternative is an allochthonous, storm-transported source for the *G. prisca*. Thus if we assume that the kukersites examined in this study of the Yeoman Formation grew as subtidal algal mats, three things are difficult to explain (Figure 3.11). First, there is a lack of algal mat micro-textures formed by *G. prisca* such as pustules, pinnacles, min-domes (as reported by Stasiuk and Osadetz, 1990; Stasiuk, 1999), even though *G. prisca* and hardgrounds are present in the examined kukersite samples. Second, one must explain how the organic matter was introduced into borings and burrows found below these algal mats and why organisms re-burrow the fill of these borings when adequate food was available at the sea floor. The borings are filled with organic-rich sediment down to depth as much as 5-10 centimeters (Figure 3.4). The boring diameters range from few millimeters to a few centimeters (Figure 3.5) and are infilled by organic-rich sediment from above. Larger-diameter borings and *Thalassinoides* would have been passively infilled with relative ease. The borings locally contain abundant skeletal fragments and lithoclasts. It is much harder to account for the dense fill of the small few millimeter diameter burrows and borings. The algal mats would have to be loosened and 'stuffed' down into the burrow, which seems quite unlikely. The rather dense packing of these boring and burrow fills is suggested by the fact that they are reworked by *Asterosoma*, *Planolites* and *Chondrites*. It would be a rather odd

adaptation indeed if a deposit-feeding organism would burrow down into the sediment, rather than burrowing through algal mats at the sea-floor.

Alternatively, if one assumes the burrows and borings were constructed penecontemporaneously with the deposition/accumulation of *G. prisca* algal mats, the borings with diameters ranging up to 2 centimeters would indicate that such a large animal lived in the substrate during periods when growth and development of the algal mat was flourishing. Animals rarely create borings much larger than themselves, making this scenario quite unlikely. Exceptions like *Siphondictyon*, a boring sponge, did not evolve until the Mesozoic (pers. comm. Pemberton, 2002). Furthermore, 2 centimeter diameter borings are quite rare. When these structures attain such a size, they more likely represent *Thalassinoides*, but then they would have to predate cementation of the hardground surface (like the pre-omission suite burrows of Bromley, 1975).

Third: How was organic matter introduced into burrows underlying these hardground surfaces? The biogenic sedimentary structures further down are soft sediment burrows and not borings (Figure 3.4a). These burrows containing abundant organic matter that can be found up to 3 meters below the hardground surface. They are generally smaller in diameter than most of the borings, do not exhibit sharp walls, and their linings contain reworked organic matter. These were not formed in a cemented substrate. This would indicate that organisms smaller than those, which made the borings in the hardground, dragged the organic matter down below the kukersitic interval.

Even if submarine cementation at the hardground surface only affected a few centimeters of sediment, it seems unlikely that an organism would burrow down beyond the cemented zone into the uncemented carbonate sediment for several meters, carrying organic material with it. The burrows 20 centimeters or so below the base of kukersites, filled with organic matter, may have been left by organisms seeking protection from predators. However, lined burrows further down from the kukersite, which are only lined with organic matter, probably predate deposition of the kukersite; locally, borings filled with kukersitic material are observed crosscutting lined burrows. Deep burrowing has been observed in the Lower Palaeozoic (Droser and Bottjer, 1989), but there seems little purpose in such a great excavation effort if the food source is at the sediment-water interface. Furthermore, if indeed the *G. prisca* is 'piped down' into the carbonate sediment by the infauna, there one should observe a maximum depth below these kukersites in which *G. prisca* are found. But this is not the case, since *G. prisca* occur in burrows throughout the upper Yeoman Formation.

It must also be noted that these burrows below the kukersites (Figure 3.4) pass from actively back-filled (*Planolites*) burrows to lined ones (*Rhizocorallium*, *Asterosoma* and *Palaeophycus*). This implies a shift from deposit-feeding to surface detritus and suspension-feeding activity, with the latter having open tubes during the life of the trace-making organism. Organisms commonly shift their behavior from deposit-feeding to filter-feeding as they approach the sediment-water interface, but not with increased depth from the sediment water interface. The opposite is observed below the lower contact of those kukersites overlying hardgrounds.

Accumulation from Transported Storm Deposits

Foster et al. (1990) suggested that kukersite intervals can be interpreted as condensed sections formed from sediment washed basinward from intertidal flats. Some properties of kukersites supporting this interpretation include: high organic content, the presence of large, well-preserved fossils, association with burrowed, bored or slightly lithified tops. But they fall short of other common characteristics of lower Paleozoic condensed sections: diverse planktonic and benthic fauna, diverse microfauna and sparse ichnofossils (Jenkyns, 1971; Loutit et al., 1988). Their limited correlatability, (i.e. that they are correlatable only within a single oil pool) may also support a condensed section interpretation. Missing kukersite beds presumably represent reworking and removal by storms or bioturbation. Another possibility is that pressure solution removed the kukersite bed, leaving behind an organic-rich stylolite. It must be noted, however, that the *G. prisca* alginite found in burrows below the hardgrounds are still difficult to explain if it was washed in by periodic storms from intertidal regions.

In some intervals, *G. prisca* material is preserved only as the lining of *Palaeophycus*, *Asterosoma*, *Rhizocorallium* and composite burrows (Figure 3.8b), with no evidence of an overlying kukersite bed. *Palaeophycus* are more commonly lined by disseminated A, and the others by disseminated B *G. prisca* alginite. If kukersites are sourced from sediment and organic matter transported basinward from an intertidal zone, those maceral types should also be present in the matrix and *Planolites* fills. In fact, both are devoid of the *G. prisca* maceral variety. Clearly, in the kukersites examined in this study, the dispersed organic matter/macerals were therefore not residing on the seafloor when the organism incorporated them into its burrow.

Planktonic Algal Bloom Model

Accumulation of kukersites from a planktonic algal bloom provides an explanation more consistent with the relationships between the burrows and the organic material. Hoffman et al. (1987), as well as Kent and Haidl (1999), suggested that *G. prisca* algal blooms can flourish to such an extent that they 'poison' and/or de-oxygenate the water column creating a zone of anoxia under the bloom or near the sediment water interface. Both the ichnology and the distribution of *G. prisca* maceral varieties support this model (Figure 3.12). During normal marine conditions (Stage 1), burrows are thinly lined by dispersed organic matter and various macerals such as acritarchs, as well as disseminated A *G. prisca* alginite (Figure 3.9a). At the onset of the algal bloom, the amount of organic matter increases in the water column, and this is also recorded in the burrow linings (Stage 2). The lining is thicker, and contains more abundant disseminated A *G. prisca* (Figure 3.9b). As *G. prisca* flourishes and the bloom advances in its growth stage, disseminated B *G. prisca* is also preserved in burrow linings (Stage 3: Figure 3.10a,b,c). The shift from disseminated A to disseminated B *G. prisca* supports increasingly favourable conditions for *G. prisca* growth, or progressive change in the life form of *G. prisca* as the algal bloom proceeds. Thicker walled, larger *G. prisca* of disseminated B clearly represent an advanced growth stage or a significant vegetative stage of the alga (Stasiuk and Osadetz, 1990). Suspension feeding and various open-tube dwelling

organisms commonly filter dissolved or particulate organic matter from the water column (Schäfer, 1972) and subsequently incorporate them into the sediment. The *G. prisca* or algal detrinite indicative of *G. prisca* origin is ubiquitous in *Palaeophycus* linings. The morphologies of *Rhizocorallium*, *Asterosoma*, and associated composite burrow systems are also indicative of suspension and surface-deposit feeding. *G. prisca* was presumably introduced below the sediment water interface as waste storage (Kotake, 1991; Bromley, 1991 and references therein). Organisms commonly shift to more complex feeding habits when there are changes in nutrient availability. It appears logical that when the water column becomes more toxic due to an algal bloom, benthic fauna would dispose of waste below the sediment-water interface so as not to further pollute the water column.

Eventually the algal bloom thrives to such a degree, that it 'poisons' the water column, halting carbonate sediment production. Modern algal blooms are known to have adverse effects on benthic fauna (Bricelj and Lonsdale, 1997), by altering water chemistry due to the release of toxins, reducing light availability or outcompeting other nutrients in the water column necessary for a healthy subtidal carbonate factory. The association of hardgrounds with kukersites supports this, because hardground formation is commonly a result of sediment bypassing (Goldring and Kaźmercziak, 1974; Brett and Brookfield, 1984). At this point, due to the availability of *G. prisca*, combined with reduced reworking of sea floor sediment by benthic fauna, kukersite beds are deposited and preserved (Stage 4: Figure 3.6a). In addition, algal blooms promote high rates of oxygen depletion in a water column, usually related to high rates of oxygen consumption by bacteria and other organisms, leading to a de-oxygenated water column. Immediately, following the bloom water column conditions may equilibrate allowing for benthic faunas to become more active and to burrow or bore into the layers rich in *G. prisca*. Physical, chemical and biological causes of these algal blooms are uncertain, but may be linked to changes in temperature, salinity, and nutrient availability (Bricelj and Lonsdale, 1997, and references therein), commonly related to seasonal variations in non-equatorial environments. The scale of cyclicity appears to be larger than a seasonal one, not to mention, during the Ordovician, southeastern Saskatchewan (Williston Basin) straddled the equator (Levin, 1994), and thus seasonal changes are attenuated. Causes of cyclicity remain to be examined. As the algal bloom dies out, this cycle ends and a new one begins. Such repeated cycles are believed to have resulted in the carbonate-kukersite cycles of the upper Yeoman Formation.

Organic laminae commonly occur within the kukersitic intervals (Figure 3.2a, 3.7a). An algal mat interpretation need not be invoked for explaining the laminated nature of the kukersites. Insolubles are often concentrated along solution seams (Wanless, 1979). Many organic laminae have the wispy nature of solution seams, often grading from laminae to microstylolites. This is of particular importance in the Yeoman Formation, which has undergone considerable pressure solution. Some laminae are indeed microstylolites when checked under the microscope. The fact that the organic laminae locally wrap themselves around *Planolites* suggests that they are a result of pressure solution.

In the non-kukersitic intervals there are concurrent burrows with and without DOM/kerogen in the fills and linings (Figure 2.10b, 2.11a, 3.8). The carbonate matrix and the deposit-feeding *Planolites* do not

contain *G. prisca* type macerals. However, those burrows, which are in connection with the seafloor, do contain *G. prisca* as fill or lining. Surface detritus feeders are known to incorporate a planktonic food source in its burrow fill and lining (Kotake, 1989). *Palaeophycus*, which are formed by suspension feeding, or serve as dwelling burrows, are lined to variable degrees by disseminated A *G. prisca* (Figure 3.3). *Asterosoma* and *Rhizocorallium*, which are also in connection with the sea floor, are lined either by disseminated A or B *G. prisca* alginite. If *G. prisca* was part of the sea floor sediment, deposited either as an algal mat or from the transport of storms as suggested by Foster et al. (1990), it would have been preserved in the *Planolites* fill or the matrix.

3.5 Conclusions

The mechanisms in which the microfossil *Gloeocapsomorpha prisca* was consumed and utilized by burrowing infauna is more consistent with the interpretation that this organism was readily available in the water column throughout the deposition of the upper Yeoman Formation. Fluctuations in abundance of *G. prisca* is recorded by the fluctuations in feeding habits of infauna represented by the trace fossils and by fluctuating abundance of *G. prisca* preserved in the sediment. Periods of lowered *G. prisca* availability are represented by the disseminated A maceral variety thinly lining the burrows. When conditions shifted to indicate that organic matter was more available, the disseminated B *G. prisca* maceral variety is also found in the burrow linings and fills. At maximum blooms, beds rich in disseminated B *G. prisca* were preserved. The ichnological and petrographic evidence both suggest that the kukersites of the Yeoman Formation were accumulated from a planktonic microfossil. Although conditions causing these blooms are uncertain, the monospecific trace fossil suite of the kukersites suggests a restriction of the sea floor.

The presence of scolecodonts in the sediment and burrows must be noted. Although, it is beyond the scope of this study, an examination of their distribution may provide an insight into the trace maker responsible for many of the Yeoman trace fossils. These jaws of ancient carnivorous worms may be identified and provide identification of the trace making organism.

Figure 3.1

Cross-Section Through Carbonate-Kukersite Cycles: Upper Yeoman Formation

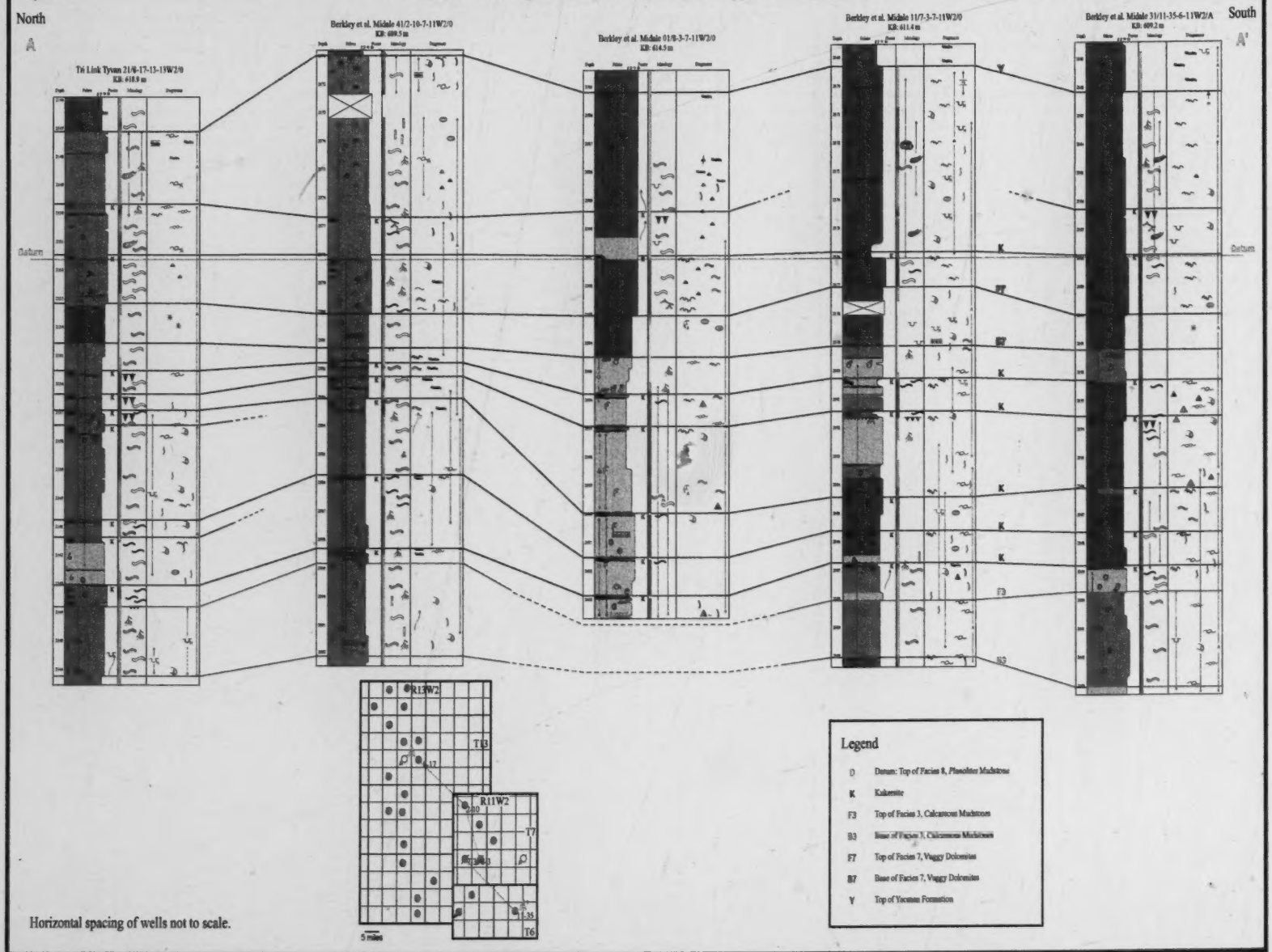
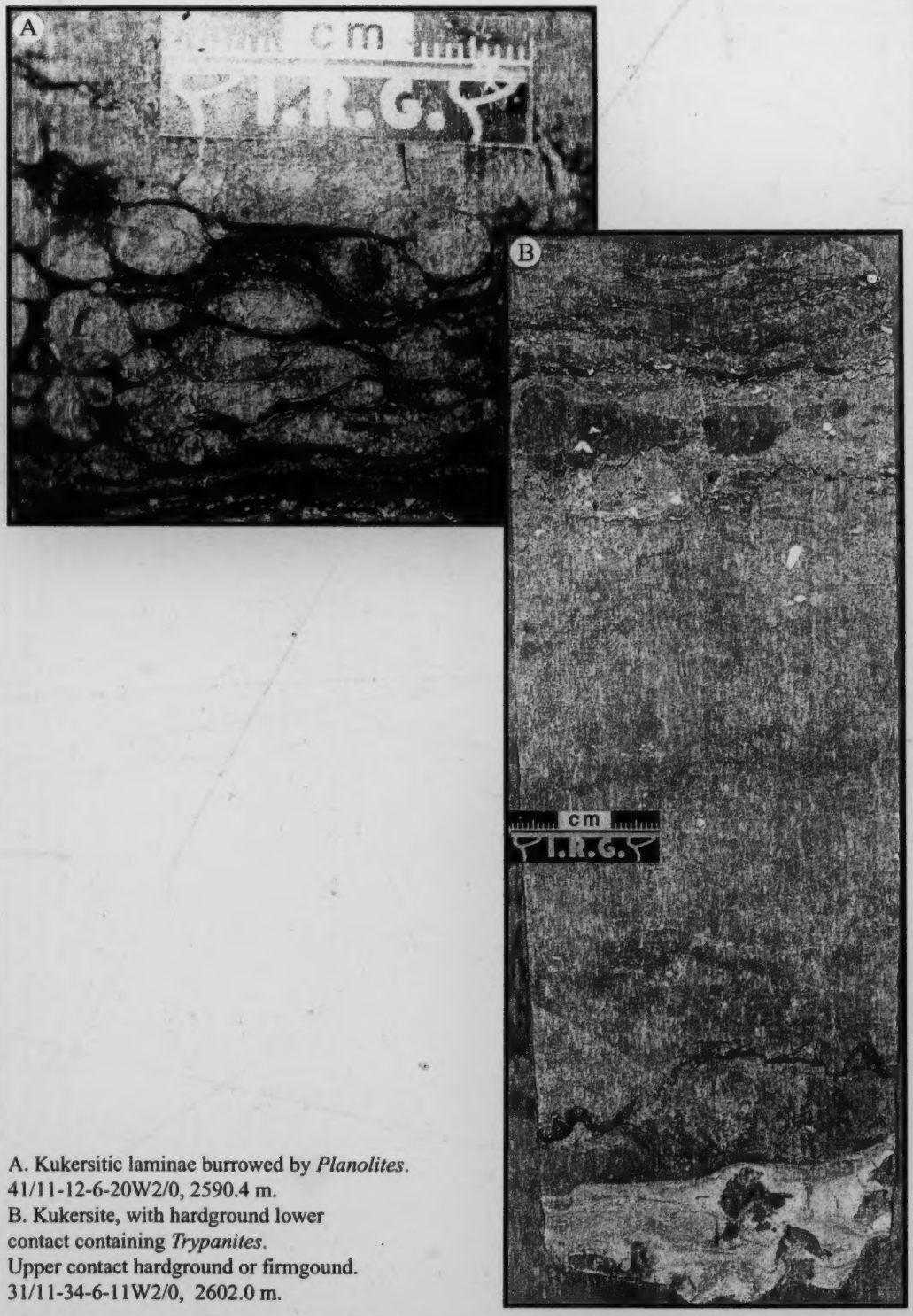
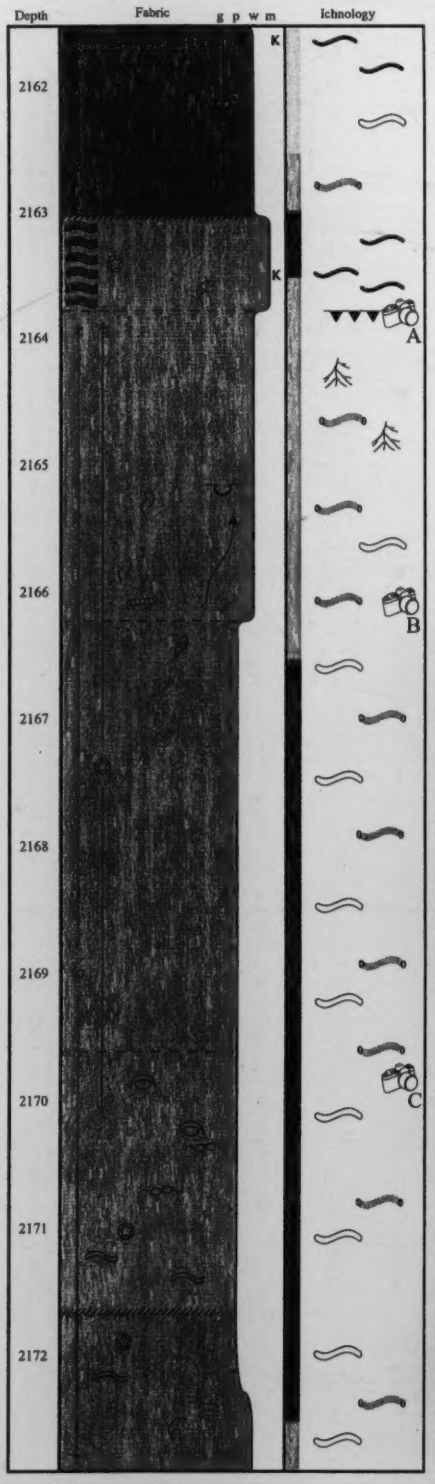


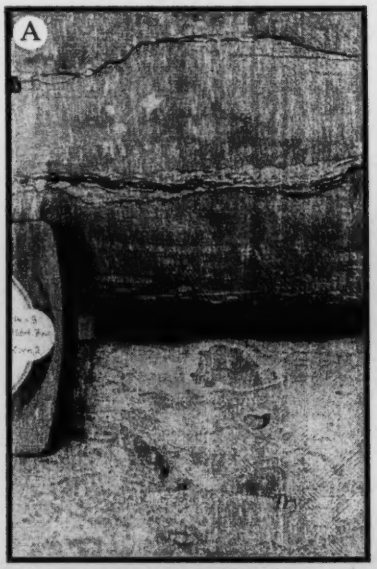
Figure 3.2 Kukersitic Laminae and Beds in the Yeoman Formation



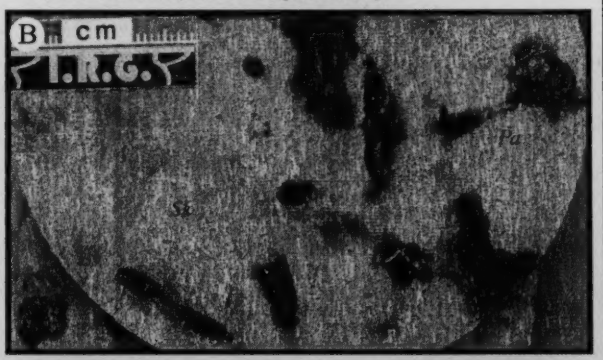
A. Kukersitic laminae burrowed by *Planolites*.
41/11-12-6-20W2/0, 2590.4 m.
B. Kukersite, with hardground lower
contact containing *Trypanites*.
Upper contact hardground or firmgound.
31/11-34-6-11W2/0, 2602.0 m.

Figure 3.3 Organics Below the First Kukersite: 21/8-17-13-13W2/0

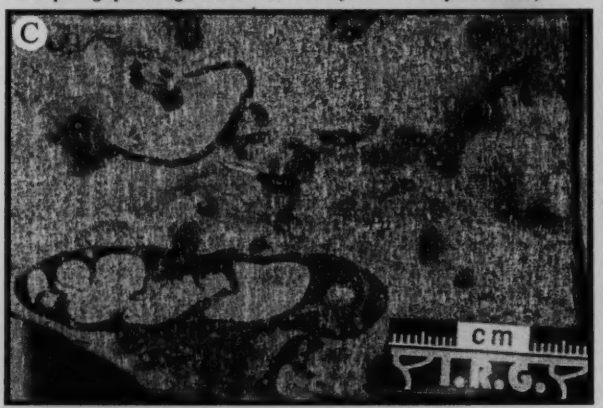




A. *Trypanites* below kukersite, *Planolites* within kukersite. Contact missing from core. 2163.7 m (uncorrected depth 2164.7 m)..

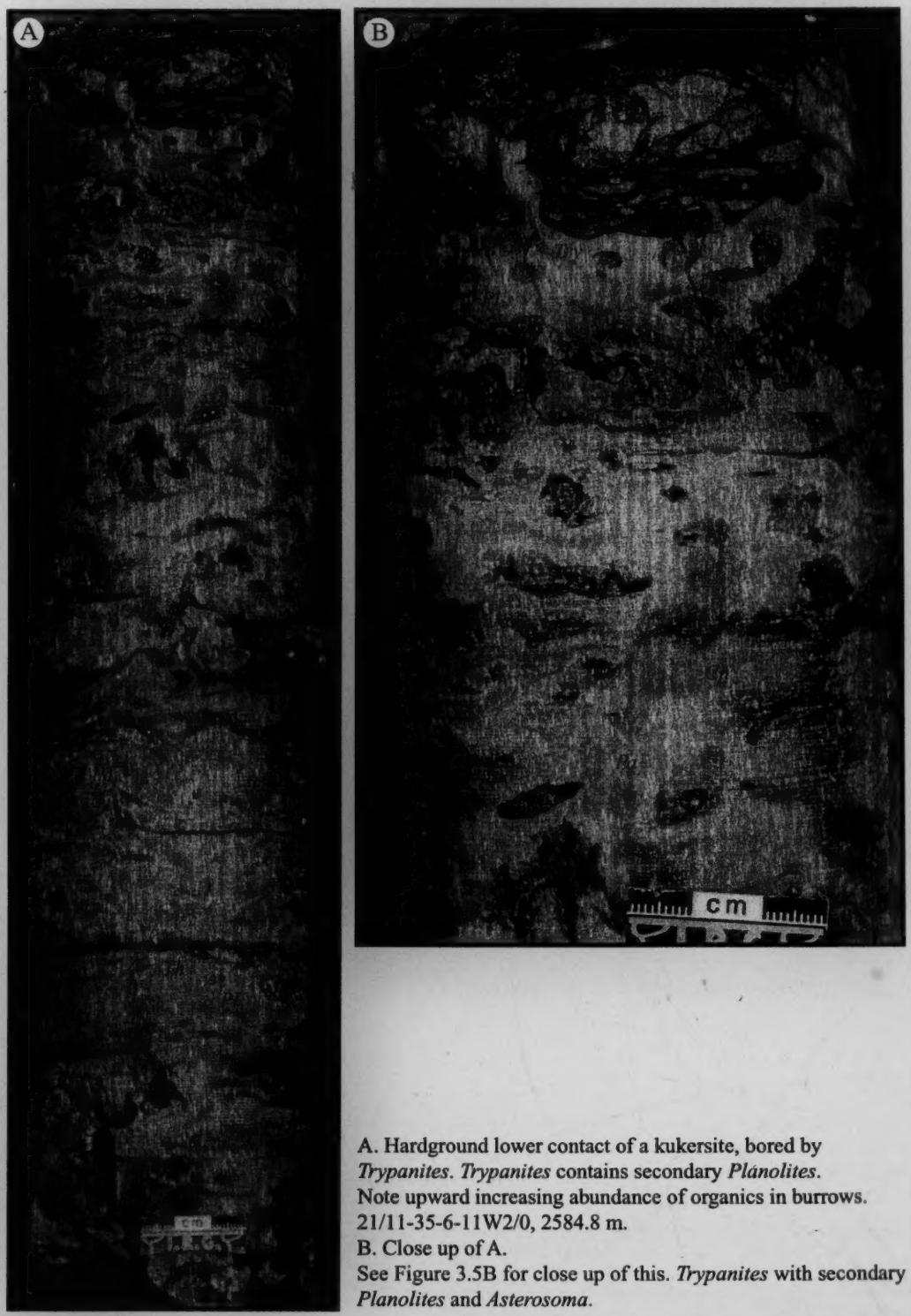


B. Increasingly abundant organic matter in burrow linings, see Figure 3.10 for microphotographs of organic matter. 2166.2 m (uncorrected depth 2167.2 m).



C. Lowermost facies with minimal organic matter in *Palaeophycus* linings, *Trypanites* in gastropod shell. 2169.9 m (uncorrected depth 2170.9 m).

Figure 3.4 Carbonate-Kukersite Cycle



A. Hardground lower contact of a kukersite, bored by *Trypanites*. *Trypanites* contains secondary *Planolites*. Note upward increasing abundance of organics in burrows. 21/11-35-6-11W2/0, 2584.8 m.
B. Close up of A.
See Figure 3.5B for close up of this. *Trypanites* with secondary *Planolites* and *Asterosoma*.

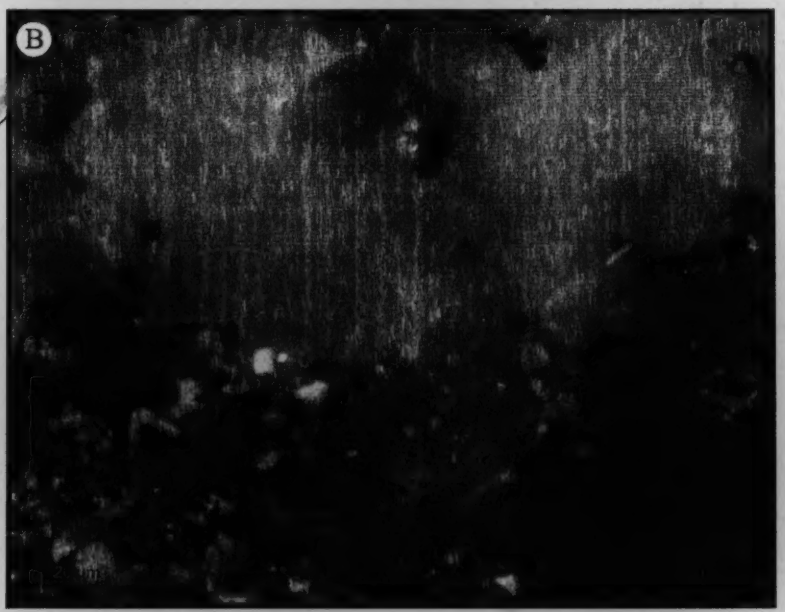
Figure 3.5 Lower Contact of Kukersites

A. *Thalassinoides* below softground base of kukersite. Kukersite burrowed by *Planolites*. 41/2-10-7-11W2/0, 2581.2 m.

B. *Trypanites* below kukersite. Fill of borings burrowed by *Planolites* and *Asterosoma*. Fill also contains lithoclasts (L), indicating lithification before kukersite sedimentation. 21/11-35-6-11W2/A, 2584.8 m.

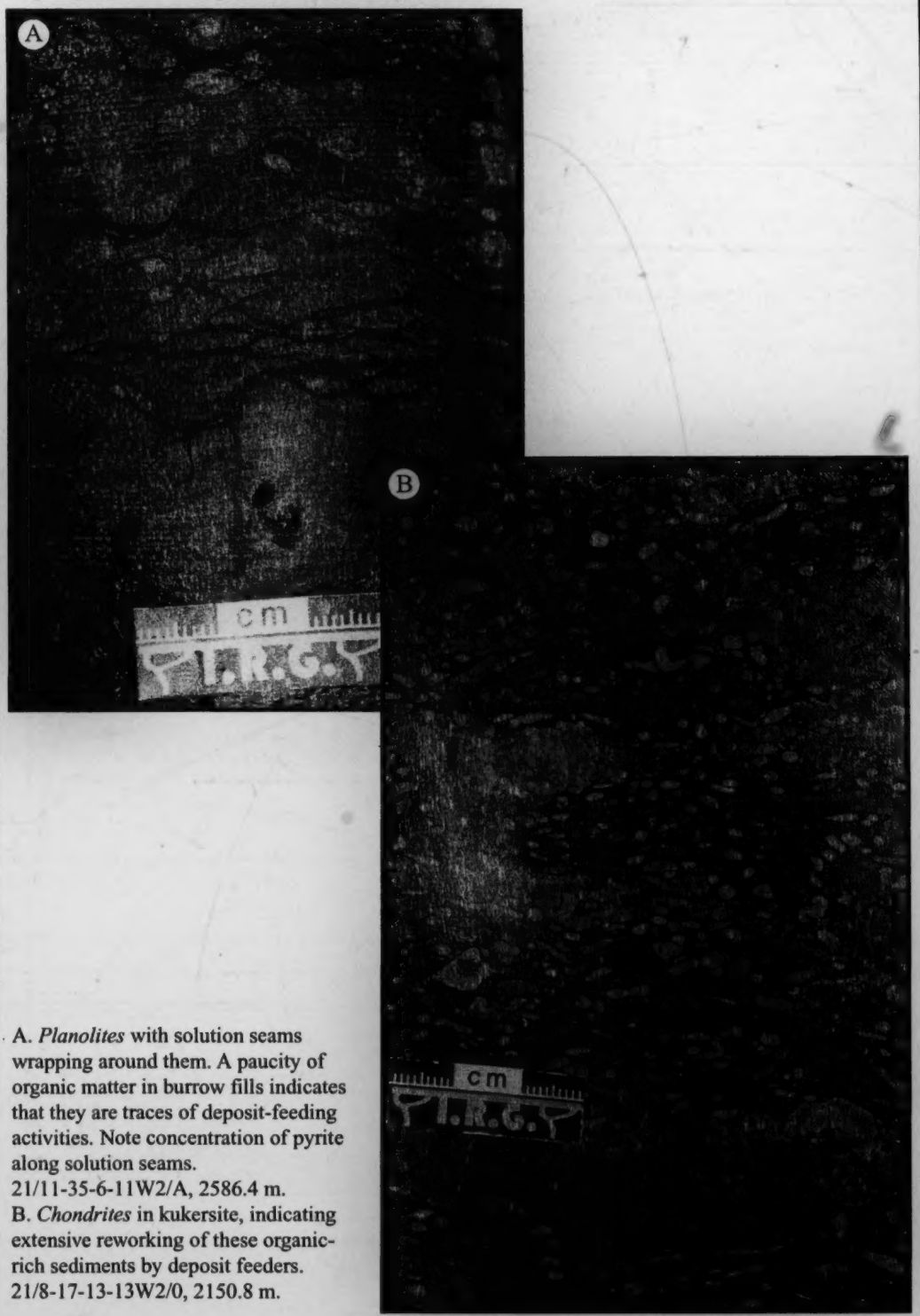
Figure 3.6 Disseminated B *G. prisca* Alginite in Kukersites

A. Disseminated B *G. prisca* alginite and algal detrinite from kukersite. Reflected UV light. Scale bar 50 μm. 11/5-8-6-19W2/0, 2710.0 m.



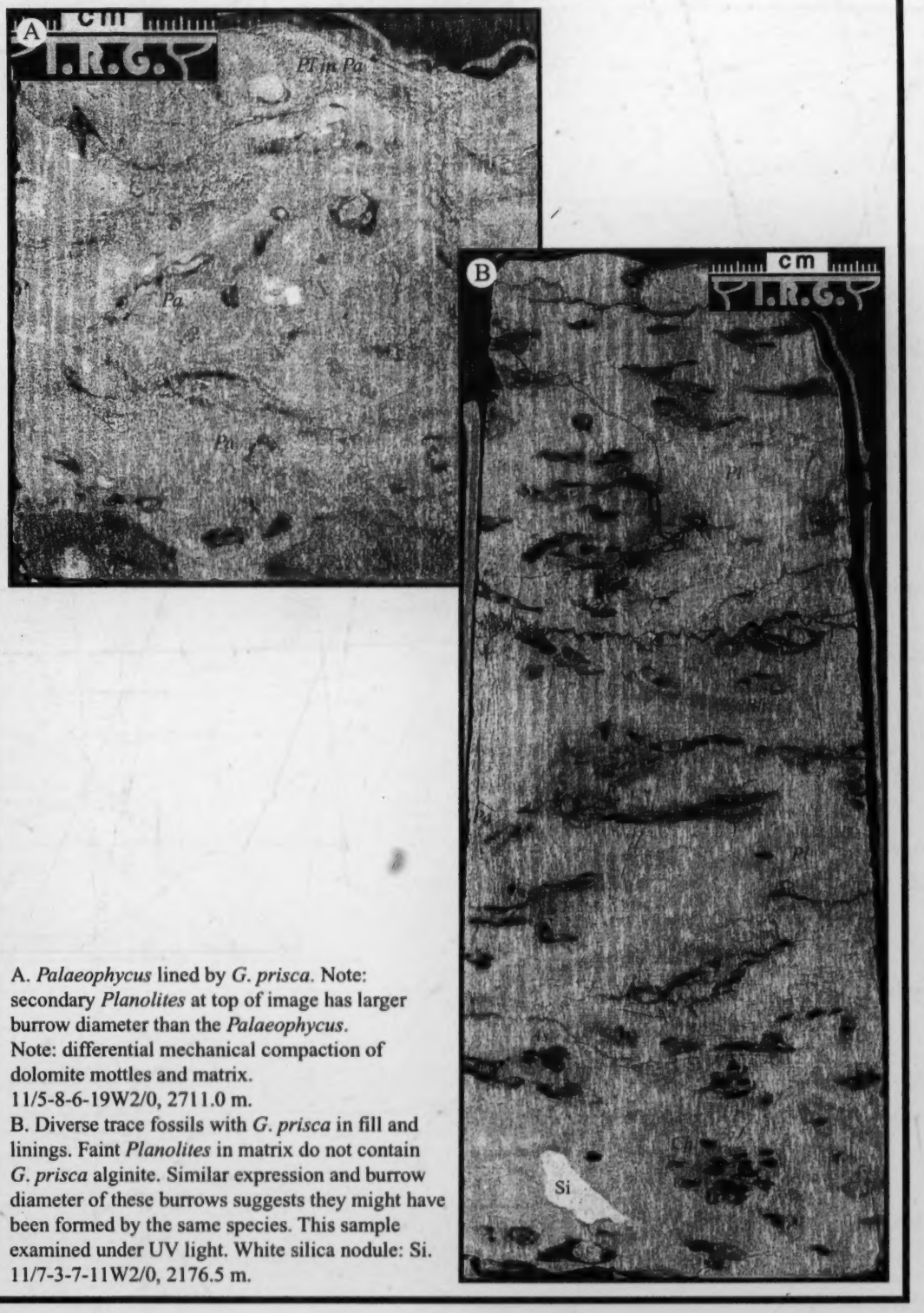
B. Fill of *Rhizocorallium* lacks organic matter. Macroscopic image Figure 2.17A. Reflected UV light. Scale bar 20 μm. 11/5-8-6-19W2/0, 2710.0 m.

Figure 3.7 Biogenic Sedimentary Structures Found in Kukersites



A. *Planolites* with solution seams wrapping around them. A paucity of organic matter in burrow fills indicates that they are traces of deposit-feeding activities. Note concentration of pyrite along solution seams.
21/11-35-6-11W2/A, 2586.4 m.
B. *Chondrites* in kukersite, indicating extensive reworking of these organic-rich sediments by deposit feeders.
21/8-17-13-13W2/0, 2150.8 m.

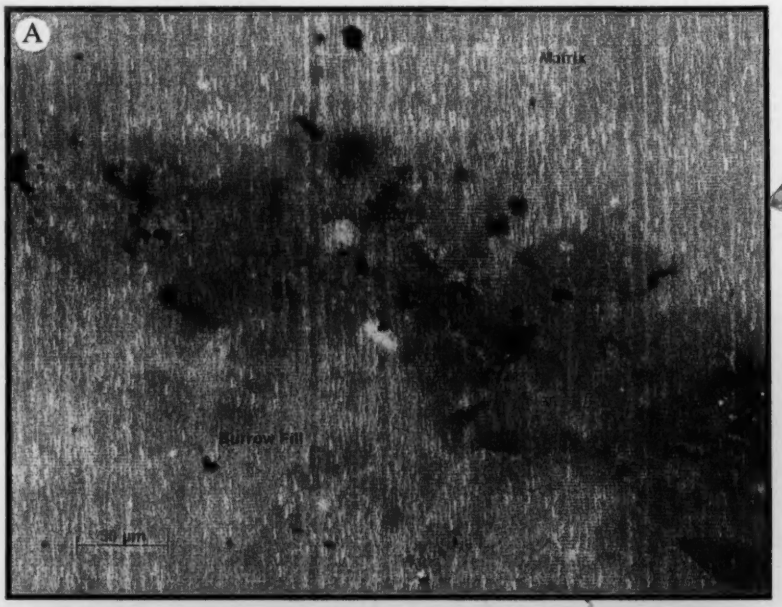
Figure 3.8 Burrows Lined with Organic Matter



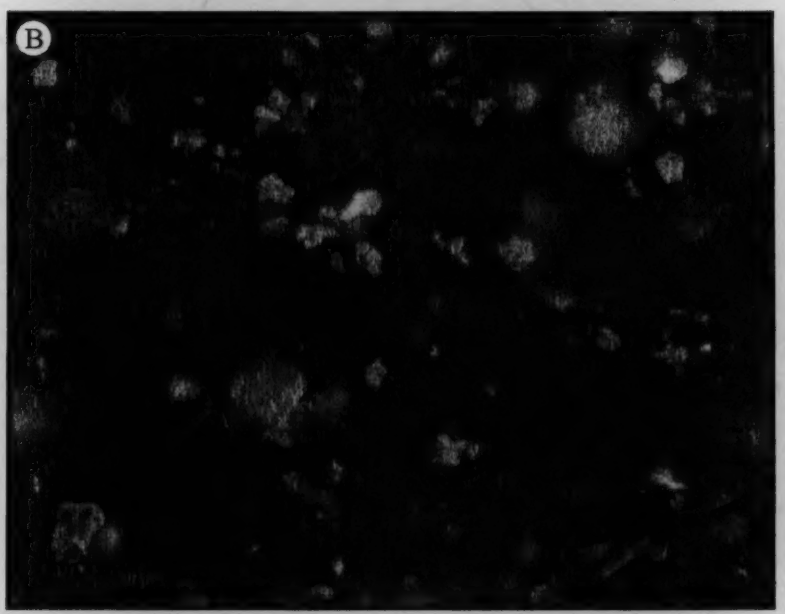
A. *Palaeophycus* lined by *G. prisca*. Note: secondary *Planolites* at top of image has larger burrow diameter than the *Palaeophycus*. Note: differential mechanical compaction of dolomite mottles and matrix. 11/5-8-6-19W2/0, 2711.0 m.

B. Diverse trace fossils with *G. prisca* in fill and linings. Faint *Planolites* in matrix do not contain *G. prisca* alginite. Similar expression and burrow diameter of these burrows suggests they might have been formed by the same species. This sample examined under UV light. White silica nodule: Si. 11/7-3-7-11W2/0, 2176.5 m.

Figure 3.9 *G. prisca* Disseminated A and B Alginite: Stages 1 and 2

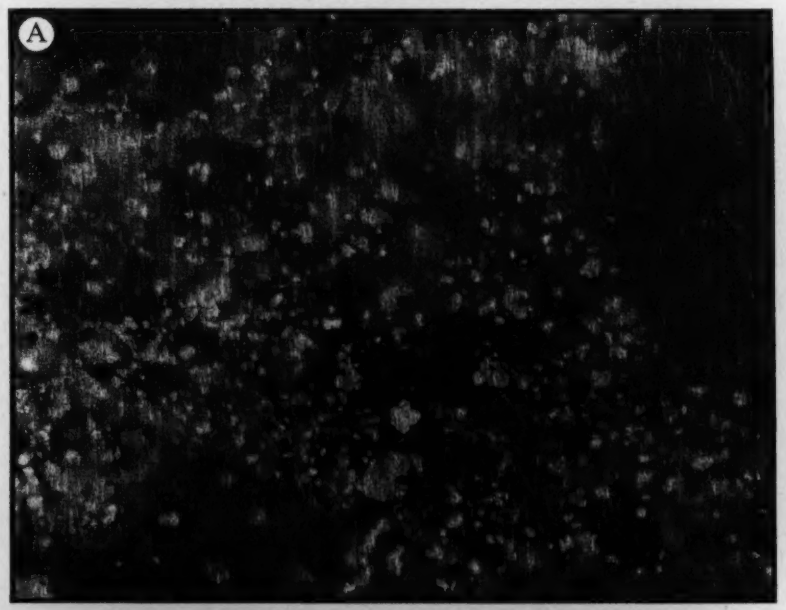


A. *G. prisca* diss A alginite lining *Palaeophycus* formed under normal conditions, Stage 1. Reflected UV light. Scale bar 50 µm. 21/11-35-6-11W2/A, 2597.3 m

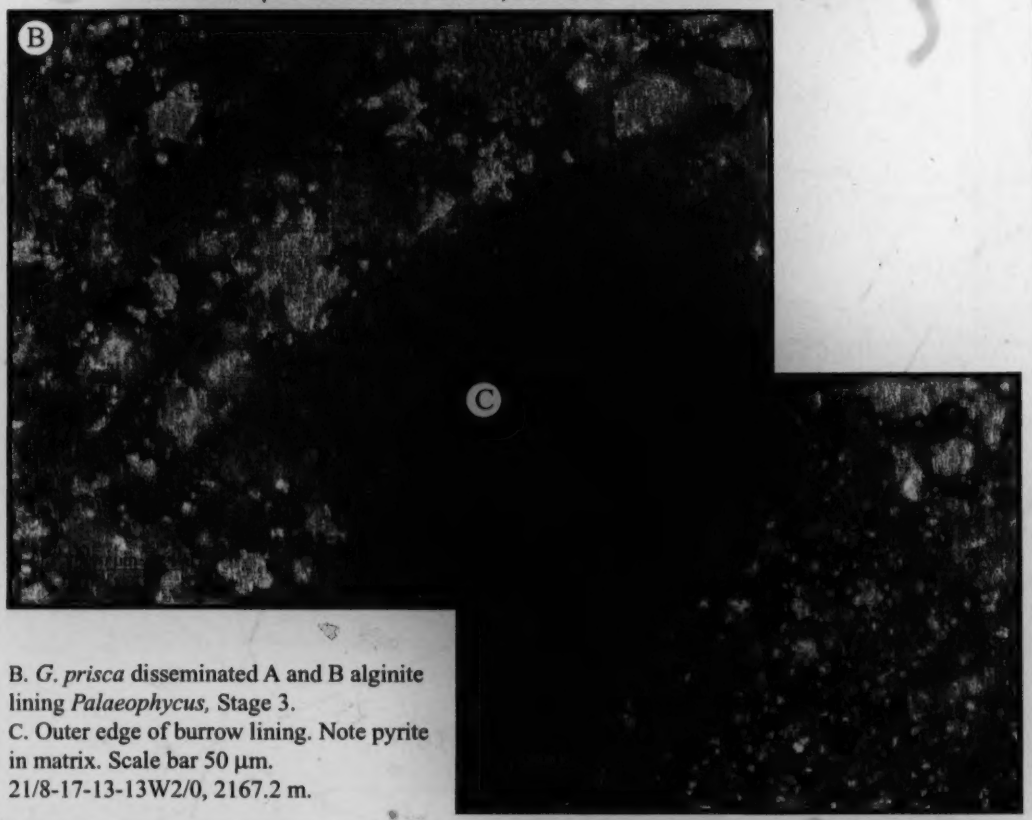


B. *G. prisca* diss A alginite lining *Palaeophycus* formed during onset of algal bloom, Stage 2. Reflected UV light. Scale bar 20 µm. 21/8-17-13-13W2/0, 2167.3 m.

Figure 3.10 *G. prisca* Disseminated A and B Alginite: Stage 3

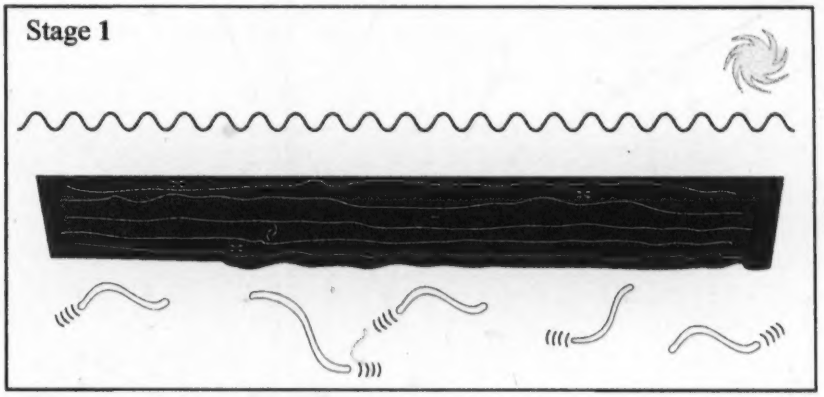


A. *G. prisca* disseminated A and B alginite lining *Palaeophycus*. Stage 3. Scale bar 50 µm. 21/8-17-13-13W2/0, 2167.2 m.

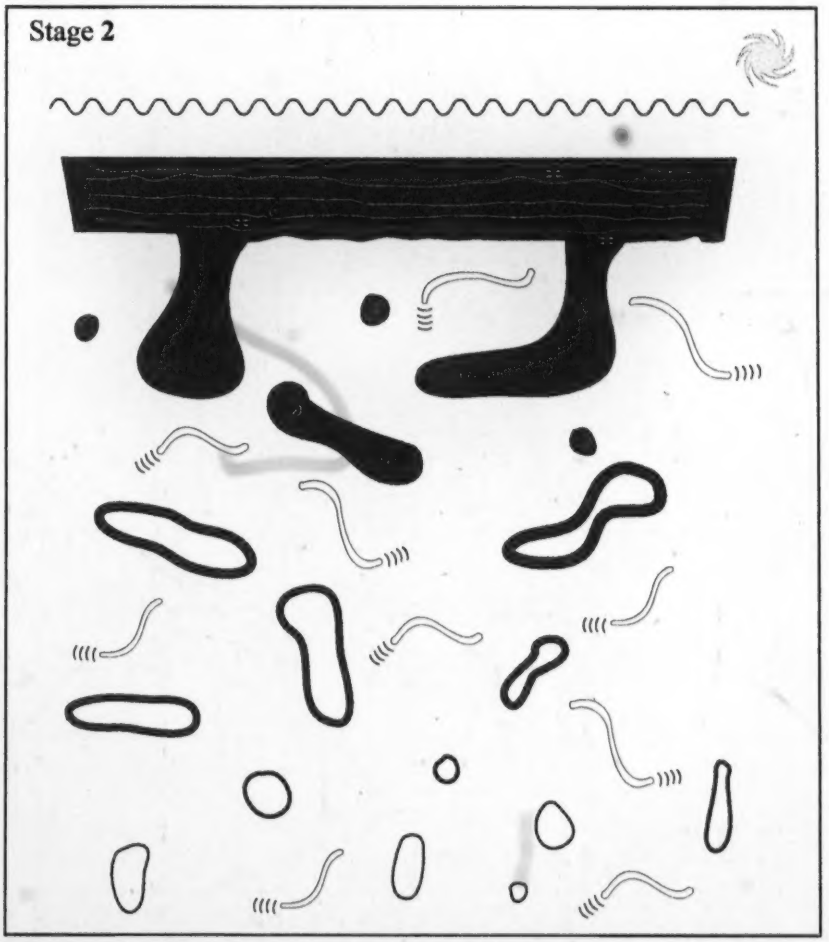


B. *G. prisca* disseminated A and B alginite lining *Palaeophycus*, Stage 3.
C. Outer edge of burrow lining. Note pyrite in matrix. Scale bar 50 µm.
21/8-17-13-13W2/0, 2167.2 m.

Figure 3.11 Accumulation of Kukersites from Algal Mat Growth

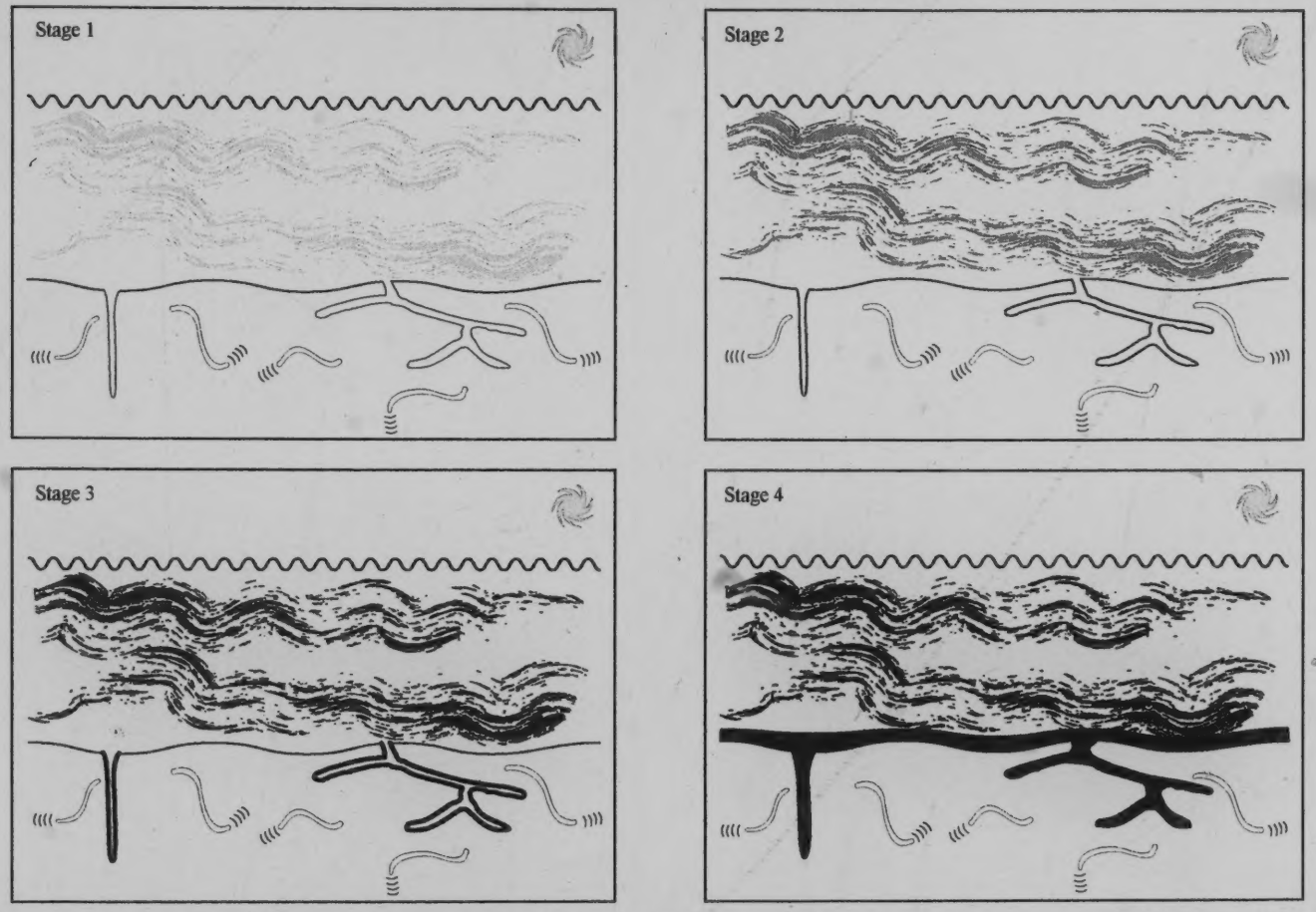


A. Growth of algal mat at sea floor.



B. Introduction of *G. prisca* alginite into borings and burrows from the algal mat. Diagrams are not to scale.

Figure 3.12 Kukersite Accumulation from a Planktonic Algal Bloom



Progressively thicker burrow linings correspond to progressively more *G. prisca* available in the water column, as the algal bloom progresses (Stages 1 - 3). Stage 4: Kukersite bed is preserved and sea-floor burrows and borings are filled with *G. prisca* - rich sediment. Not to scale.

CHAPTER 4. FACIES AND DEPOSITIONAL HISTORY OF THE YEOMAN FORMATION

4.1 INTRODUCTION

Sediments of the Upper Yeoman of Southeastern Saskatchewan contain fluctuating trace fossil assemblages, the distribution of which were likely controlled by subtle changes in sedimentation, water energy, oxygenation, substrate consistency and, most importantly, nutrient availability. The purpose of this chapter is to describe the sedimentary facies, and to suggest how their vertical succession indicates gradual restriction superimposed upon cyclical carbonate-organic accumulation during deposition of the Yeoman Formation. Yeoman facies are subdivided based on changes in sedimentary fabric, allochem composition and trace fossils, but since many original fabrics have suffered diagenetic obliteration, the trace fossils, commonly enhanced by diagenesis, prove to be the most valuable criteria for distinguishing facies. This is consistent with the inverse preservational model of Rhoads (1975), in that the diversity of trace fossils does not correlate with the diversity of fossils. It is believed that traditional clastic oriented facies models (Seilacher, 1967, Frey and Pemberton, 1984; Pemberton et al., 1992) cannot be directly applied in carbonates, and a new modified model must be constructed for sedimentary packages that accumulate from purely carbonate deposition.

4.2 TRACE FOSSIL FACIES MODELS AND CARBONATES

Trace fossils reflect the sediment-mediated behaviours of organisms, and therefore the preserved record of the various environmental constraints acting on the benthic community (Seilacher, 1967; Pemberton and Frey, 1984; Bromley, 1990; Pemberton et al., 1992). Acquisition of nutrients is of course essential to the survival of all living organisms, hence feeding behaviours are the most sensitive to environmental changes. In the classic ichnofacies scheme of Seilacher (1964; 1967), bathymetrically defined gradients in nutrient availability, commensurate with changes in energy-level and sediment grade, exert an underlying control on the trophic structure of trace making communities (see Pemberton et al., 1992 for a recent review). In nearshore clastic settings, transitions from *Skolithos* ichnofacies to *Cruziana* ichnofacies thus reflect an energy/substrate mediated shift in the relative partitioning of suspended versus deposited food resources. However, in a shallow carbonate platform setting, such as envisioned here for the Yeoman Formation, a fundamentally different set of nutrient-regulating conditions exists.

The first consideration, in examining nutrient availability in epicontinental carbonate settings dominated by bioclastic sediments, is the of the source of these sediments. These vast epeiric seas are believed by some to have been exceedingly shallow (average depths of < 10 meters), with fair-weather

wave base less than 5 meters (Tucker and Wright, 1990). Although, exact water depths remains debatable, it is generally agreed that these Yeoman sediments were deposited subtidally. Sediment production was from the subtidal carbonate factory (James, 1979), these being classic open marine, subtidal facies: i.e. thoroughly burrowed bioclastic wackstones (Wilson, 1975). Now consider the nutrient sources: these sediments are predominantly composed of the skeletal remains of organisms. Their soft, "easily decaying parts" were not readily preserved. Detritus was abundant at the sea floor where such gastropods, echinoderms, trilobites, corals and bryozoans lived and died. As observed in modern studies, many of the aforementioned organisms live in zones where water is turbid enough to provide nutrients. Hence, the 'subtidal carbonate factory' is rich from both benthic (decaying organic matter) and planktonic (zooplankton and macerals) sources. Benthic fauna can "choose" from a variety of nutrient sources. There is no strong correlation between grainsize and nutrient availability, nor water energy and grainsize. Their paleo-ecosystem must thus be closely examined for interactions amongst biota. Unfortunately, no modern analogue exists for the vast Lower Paleozoic epicontinental seas, and fossil body and trace remains must be utilized together to obtain the most information possible. Concepts, such as ichnofacies models, from clastic depositional environments must be used with caution.

4.3 Facies of the Yeoman and Herald Formations

Correlation of well logs and cores of the Yeoman Formation show these sediments are correlatable within each of the oil pools. Similarity in the vertical facies succession amongst Midale, Tyvan and Ceylon is consistent with the expected lateral continuity of epicontinental platform carbonates. In the examination of cores and thin sections, twelve facies are subdivided based on fabric, allochems and trace fossil suites (Table 4.1, 4.2). Due to variable matrix dolomitization, lithology is not facies dependent, but clearly recognizable markers allow the establishment of laterally equivalent zones (Figure 4.1 – 4.4). All Yeoman facies are dolomitized to some degree, however the degree is variable vertically within a single core and between adjacent wells (Figure 4.5, 4.6). Ceylon pool sediments show the greatest contrast to the other two pools, in that the facies are not observed in the same order (Figure 4.7). Facies 1 through 9, belong to the Yeoman Formation and these are the focus of this study. The remaining 3 belong to the Herald Formation, Lake Alma Member. The Yeoman and Herald Formations are subdivided based on the following facies:

Table 4.1 Facies of the Yeoman and Herald Formations

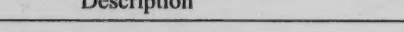
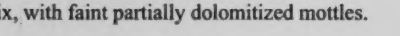
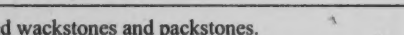
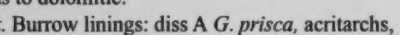
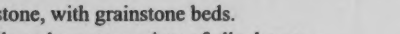
	Facies	Description	Occurrence	Interpretation
1.	Echinoderm-Rich Mudstones and Wackstones	Massively bedded mudstones and wackstones. Allochems predominantly ❂ and 6 debris. Calcareous matrix, with faint partially dolomitized mottles. *Pl* *Tr*, containing secondary *Pl* and *Pa*.	Lowermost facies. Penetrated in only the deepest wells. Observed only at Ceylon and Midale.	Low energy subtidal platform. Circulation limited to offshore currents and storm activity. Low sedimentation rate.
2.	Echinoderm-Rich Wackstones and Packstones	Massively bedded wackstones and packstones. Allochems dominatedly ❂, but also  Matrix calcareous to dolomitic. *Tr*, *Pl*, *Pa* and *Sk*. Burrow linings: diss A *G. prisca,* acritarchs, Leiosphaeridiai and zooplankton (chitinizoans, scolecodonts).	Lowermost facies. Penetrated in only the deepest wells. Observed at Ceylon, Tyvan and Midale.	Low energy subtidal platform. Increased circulation to sustain suspension feeding organisms. Increased sedimentation rate.
3.	Calcareous Mudstone	Calcareous mudstone, with grainstone beds. More macrofossils and greater variety of allochems:  *Pl*, *Pa*, *Ch* and *Sk*. Burrows linings dominated by diss A and B *G. prisca.*	Located below the onset of the carbonate-kukersite cycles at Tyvan and Midale.	Low energy subtidal platform. Increased sedimentation rate. Common storm activity. Onset (Stages **2** and **3**) of *G. prisca* algal blooms.
4.	Kukersites	Black or reddish-brown organic-rich mudstones. > 90% organic content *G. prisca,* dominantly diss B type. Allochems:  *Ch* and *Pl*, locally *Rh* and *As*. Commonly dolomitized.	Uppermost 1/4 of the Yeoman Formation Maximum: 9 beds at Tyvan, 7 at Midale and 6 or 7 at Ceylon.	Low energy subtidal platform Stage **4** of *G. prisca* algal blooms Resulting in decreased carbonate sedimentation.
5.	Nodular and Blurry-Mottled Mudstones	1-2 m thick beds of blurry and nodular mottled mudstone. Allochems: ❂ 6  *Pl*, *Th*, some with secondary *Pl*, *Pa* and *Ch*. Generally extensively dolomitized. Abundant halite hopper molds.	Uppermost 1/4 of the Yeoman Formation between kukersites.	Low energy subtidal platform. Circulation limited to offshore currents and storm activity.
6.	Wackstones Containing Composite Burrow Systems	Dominantly wackstones with great variety of allochems:  Composite burrows, *Rh*, *Th*, *As*, *Pl*, *Pa* and *Ch*. Organic matter in burrows dominantly diss A and diss B *G. prisca.* Calcareous or dolomitized matrix.	Uppermost 1/4 of the Yeoman Formation between kukersites Observed at Ceylon, Tyvan and Midale.	Low energy subtidal platform. Circulation limited to offshore currents and storm activity. Stage **3** of *G. prisca* algal blooms.

Table 4.2 Facies of the Yeoman and Herald Formations

	Facies	Description	Occurrence	Interpretation
7.	Vuggy Packstones	rich packstones, with abundant grainstone lenses. Allochems: Medium burrow density, *Pl, Pa* and *Th*. Always dolomitized.	Occurs below facies 8, in carbonate-kukersite cycles. Not observed at Ceylon.	Higher water energy. Common storm activity indicated by common storm beds.
8.	*Planolites* Mudstone	1-2 m thick, grey or tan mudstone. Allochems: High burrow density, consisting exclusively of *Pl* and *Ch*. Locally contains *Pa* at Ceylon. Abundant early diagenetic nodules.	One 2-3 m bed at Tyvan and Midale. Several < 2 m beds at Ceylon in carbonate-kukersite cycles.	Low sedimentation rate and water energy. Extensive reworking. Lowered oxygen levels at sea-floor. Flooding surface.
9.	Stylo-Mottled Mudstone	Wackstones and mudstones, with grainstone beds. Abundant , other allochems: Abundant *Rh* and composite burrow systems. *Pa, Pa, Ch* and *Sk*. Upward decrease in abundance of organic matter.	Uppermost Yeoman facies at Midale and Tyvan. Distinct stylo-mottling and silica precipitation not observed at Ceylon.	Low energy subtidal platform. Increased reworking of sediment. Stages **2** and **3** of *G. prisca* algal blooms.
10.	Peloidal Grainstones and Boundstones	Highly variable grainstones, boundstones and packstones. Allochems: and abundant . *Pl* common at base, hardgrounds bored by *Try*.	Above facies 6 at Ceylon. Above facies 9 at Tyvan and Midale.	Represents water shallowing above fair weather wave base. More restricted conditions: decrease in abundance and size of burrows.
11.	Laminated Dolomitic Mudstones	Thinlybedded and laminated dolomitic mudstone. Contains organic laminae and solution seams. Base interbedded with facies 10.	Above facies 10. Observed at Tyvan, Ceylon and Midale.	Subaqueous, evaporative conditions.
12.	Nodular Anhydrite	Massively bedded, blue nodular anhydrite. Base interbedded with underlying dolomite.	Above facies 11. Observed at Tyvan, Ceylon and Midale.	Primary anhydrite. Precipitated subaqueously in a restricted, hypersaline environment.

Facies 1. Echinoderm-Rich Wackstones and Mudstones

Facies 1 is found only in the lowermost Yeoman, and therefore it is only penetrated in a few wells. Since it is the deepest facies penetrated and the lower contact is not observed, the absolute thickness can not be determined in core. The uniform nature of the well logs, suggests that this facies comprises approximately 2/3 of the Yeoman Formation, reaching over 30 meters in thickness. Predominantly, it consists of massively bedded mudstones and wackstones, with echinoderm debris making up most of the skeletal fragments (Figure 4.8). Occasionally rugose corals, gastropods, trilobites and brachiopods can be found in this facies, but overall facies 1 lacks macrofauna. Many allochems are < 2 millimeters and require magnification for identification. Fragmentation of allochems is high. Biogenic sedimentary structures consist of faint *Planolites*, which are commonly only visible on a freshly slabbed surface. These occasionally have faint dolomitic mottles around them.

This zone also contains *Trichophycus* (Figure 2.9), thought to be the feeding burrows of small trilobites (Seilacher and Crimes, 1969). These large burrows have thin organic-rich linings, or stylolites at their walls. Their fill greatly contrasts the host sediment, suggesting that these may represent concealed bedding contacts. The different and better preserved allochems in the *Trichophycus* may be explained by one of two possibilities: Either these are the remains of animals, which could not be preserved at the sea floor, but the sheltered burrow environment allows their preservation. The higher proportions of organic-matter/kerogen in the burrow fill supports this. An alternate interpretation is that they are storm deposits, which fill open burrow systems, and were thus preserved. The overlying beds were removed or reworked, and thus not preserved. Deposit-feeding *Planolites* and *Chondrites* have re-burrowed the *Trichophycus* fills. The lower organic matter content of the *Planolites* fill suggests that the organism burrowed into the *Trichophycus* for higher nutrient content of the sediment. The sharp wall of these burrows suggests they were formed after some sediment dewatering and lithification. Facies 1 gradually grades into Facies 2.

Facies 2. Echinoderm-Rich Packstones and Wackstones

The differences between facies 1 and 2 are subtle, however, indicative of some changes in the depositional environment. Facies 2 occurs above facies 1, and in several intervals between the kukersites beds. Below the carbonate kukersite cycles, facies 2 is up to 13 meters thick, but interbedded with the kukersites, it has a maximum thickness of 3 meters. Fabrics are generally mudstones and wackstones, locally there are packstones. The sediments generally have a lower mud content than Facies 1. Facies 2 is also massively bedded and rich in echinoderms. Their relatively greater abundance compared to the other types of fossils, may be a result of better preservation potential of echinoderm debris. The single crystals appear to be more resistant to the dolomitization and recrystallization, which has destroyed much of the original sedimentary fabrics. Other fauna consists of gastropods, brachiopods, bryozoans, trilobites, tabulate and rugose corals, which are commonly disarticulated, fragmented and < 2 millimeters in size. Macrofauna is rare, and gastropods, cephalopods, large brachiopods, rugose and tabulate corals are most

commonly found in the Tyvan pool. Commonly the macrofauna are larger (up to several centimeters) and better preserved than in Facies 1. Some of these large shells were bored by *Trypanites* (Figure 4.9a).

Ichnofauna consists of *Palaeophycus* and *Planolites*, with similar diameters, ranging from microscopic (0.25 millimeters) to 5 millimeters (Figure 4.9b,c). This zone also contains some *Trichophycus*. Mottles in this zone have been interpreted as a diagenetic haloes, which have formed around the *Palaeophycus* and *Planolites*. In all three examined oil pools, the dolomite mottles have been found to contain some type of causative burrow.

Facies 2 are also found in the uppermost ¼ of the Yeoman Formation, which is characterized by carbonate-kukersite cycles. *Palaeophycus* and *Skolithos* in this interval have thicker linings, which are comprised of *Gloeocapsomorpha prisca* disseminated A type alginite (*sensu* Stasiuk and Osadetz, 1990), but commonly also contain other maceral varieties (spiny, acanthomorphic acritarchs, Leiosphaeridiai) and zooplankton (chitinizoans and scolecodonts). Allochems are typically microscopic and these contain more bryozoans, trilobites and brachiopods in the calcareous intervals. In undolomitized intervals these are better preserved than in facies 1. The trace fossil assemblage suggests that the water energy was high enough to support filter-feeding behaviour.

Facies 3. Calcareous Mudstones

Facies 3 is observed only in the Midale and Tyvan pools. These sediments are represented by a calcareous mudstone, with local 2-3 centimeter grainstone beds (Figure 4.10, 3.3b). The matrix was not susceptible to dolomitization. Combined with the low porosity development, the calcareous mineralogy makes this 2 or 3 meter thick zone easily recognizable on well logs (Figure 4.1 – 4.3). This facies is not identified or penetrated at Ceylon (Figure 4.6). The allochems, trace fossils and overall appearance are very much similar to Facies 1 and 2, however, the sediments are generally muddier. There is an increase in the abundance of macrofossils (generally still < 1 centimeter in size), notably gastropods. Other allochems are crinoids, trilobites, bryozoans, and brachiopods. The most significant difference is the noted change in the burrow pattern. The burrows, although more distinct in this zone, have a lower density. The burrow walls of *Palaeophycus* are thicker and contain more organic matter/kerogen. A higher proportion of the organic matter, compared to facies 2, consists of *G. prisca* alginite. The top of this facies contains abundant disseminated B as well as disseminated A *G. prisca* alginite. Their appearance is also accentuated by the presence of pyrite along the burrow lining. Branching *Chondrites* are much like Osgood's (1970) type A *Chondrites*, which have greater vertical than horizontal extent (Figure 2.8). The matrix is found to contain some undolomitized *Skolithos*, lined by allochems, suggesting that the water energy is high enough for filter feeders to colonize the substrate before lithification.

Carbonate – Kukersite Cycles

Above Facies 3, the uppermost portion of the Yeoman Formation, is characterized by the carbonate-kukersite cycles described in chapter 3. Kukersites are correlatable within a single oil pool, as is

the carbonate sediment in between them (Figure 3.1). The carbonate sediment in between them varies between facies 2, 5, 6, 7, and 8 (Figure 4.2 – 4.4).

Facies 4. Kukersites

Facies 4, the focus of chapter 3, are black or dark red organic-rich mudstones with the maceral variety dominated by *Gloeocapsomorpha prisca* (Figure 4.11). Lower maturation kukersites (yellow brown to red rather than black in core) which have not reached the oil window contain better preserved sedimentary structures compared with those of higher maturity. These 10-20 centimeter beds are black at Midale and Ceylon, and red at Tyvan. Commonly, kukersites have been dolomitized. Locally, they contain thin shell lags of trilobites, corals, and ostracods. Trace fossils generally consist of *Chondrites* and *Planolites*, but at Ceylon, *Rhizocorallium* were also observed.

Hardgrounds and Firmgrounds

The carbonate facies (facies 2, 5, 6, 8 and 9) between the above and below the kukersites commonly contain firmgrounds burrowed by *Thalassinoides* (Figure 3.5a), or hardgrounds bored by *Trypanites* (Figure 3.5b). These hardgrounds generally occur at the lower contact of kukersites, but also are found intermittently between carbonate sediments (Figure 2.12). Classification of the type of hardground was not possible, because the large-scale, outcrops exposures are necessary to determine criteria for classification (Fürsich, 1979 *in* Brett and Brookfield, 1984). No encrusting biota is observed. *Thalassinoides*, which may represent pre-omission suite burrows, are believed to have been formed by any of the following organisms: polychaetes, echiurids, arthropods, echinoderms or burrowing bivalves. Possible trace producers for the *Trypanites* include polychaetes and boring bivalves (Goldring and Kaźmierczak, 1944; Brett and Brookfield, 1984).

Facies 5. Nodular and Blurry-Mottled Mudstones

A mudstone, locally wackstone matrix, with mudstone mottles characterizes facies 5. Facies 5 is generally 1 meter thick, with gradational or stylolitic contacts. Commonly, these zones are fully dolomitized. At the Berkley et al. Midale 41/2-10-7-11W2/0 well, which was not completely dolomitized, both the matrix and the mottles are mudstone, suggesting that these sediments were deposited as mudstones (Figure 4.12). These branching mottles therefore appear to represent *Thalassinoides* networks and/or large *Planolites*. Causative burrows are rare to non-existent within these mottles, and one may argue that diagenesis has destroyed them, but they are also absent in the undolomitized well. At the 41/2-10-7-11W2/0 well, the cryptocrystalline calcareous matrix contains less than 5% allochems, which consist of ostracods, brachiopods, echinoderms, and some unidentifiable allochems. The occasional packstone pocket is also found, which contains abundant gastropods and brachiopods. Large *Thalassinoides*, some containing secondary *Planolites*, *Palaeophycus* or *Chondrites*, can be found in this facies. Penecontemporaneous diagenetic features are common. For example, halite hopper molds are found in the dolomite mottles, and

these must grow prior to sediment lithification, so that the growth of the crystals can displace the adjacent sediment. Evidence of halite precipitation suggests periods of penecomtemporaneous hypersalinity.

Facies 6. Wackstones Containing *Rhizocorallium-Asterosoma* Assemblages and Composite Burrows

On first appearance these sediment appear very much like the other facies. Facies 6 is made up of 2 to 3 meter thick beds of wackstones and packstones, but locally contains 2-3 centimeter mudstone and grainstone beds (Figure 4.13). These beds generally occur between kukersites 1 to 2 meters apart. They contain a wide range of allochems consisting of gastropods, echinoderms, rugose corals, ostracods, brachiopods, trilobites and bryozoans. Locally, an interval may be dominated by one fossil type. Most of the allochem debris is disarticulated, but rarely fragmented. Generally, allochems have better preservation than facies 1, 2, 5 and 7, even in dolomitized intervals. In some grainstone lenses, the gastropods are well preserved. Generally the skeletal debris is < 2 millimeters, and requires microscopic identification; but in some intervals, especially in thin few centimeter beds, macrofossils are also abundant. The carbonate sediment commonly contains faint *Planolites*, which may only be evident on a freshly slabbed surface. The organic-rich linings of burrows in this facies are thicker and contain abundant *G. prisca* alginite, both of the disseminated A and disseminated B maceral variety (*sensu* Stasiuk and Osadetz, 1990). Generally, as the burrow linings become thicker upwards in this facies, the proportion of disseminated B to disseminated A *G. prisca* increases. Closer examination of burrow linings shows that many have several concentric walls (see chapter 5 figures), some have meniscate fills, and many exhibit the nature of having reworked the same sediments repeatedly. Enough evidence exists to show that rather than *Palaeophycus*, many of these lined burrows represent *Asterosoma*, *Rhizocorallium* or composite burrows. The faint *Planolites* in the matrix do not appear to be crosscut by the lined burrows, but rather the two burrow types seem to have been formed concomitantly.

Facies 7. Vuggy Packstones

At Tyvan and Midale the top of this facies lies below facies 8, and it has been extensively altered by complex diagenesis that has cause precipitation of sucrose dolomite and the dissolution of vugs (Figure 4.14). This facies is 1 to 2 meters thick and has either gradational or stylolitic upper and lower contacts. Although sedimentologically this facies does not differ greatly from facies 2, it does warrant a distinction. This zone has been extensively dolomitized in all the intervals and commonly contains abundant fractures and vugs. Here distinction between matrix and mottle may be arbitrary. This facies contains a 2 centimeter crinoid lens that can be correlated throughout the Midale pool, and perhaps even the Tyvan. The allochems are almost exclusively crinoids, but as stated before, these are most resistant to dolomitization, and thus their dominance may be an artifact of preservation potential. *Planolites* and *Palaeophycus* can locally be distinguished in this facies, but they are usually only visible on a freshly slabbed surface. This facies is not observed at the Ceylon pool, but since this interval may be a result of diagenesis that is expectable given the distance of that pool.

Facies 8. *Planolites* Mudstone

This zone consists of a mudstone thoroughly burrowed by *Chondrites* and *Planolites* (Figure 4.15). Allochems are rare, in some wells lenses of well-preserved ostracod, brachiopod and trilobite debris are found. Burrows do not always exhibit evidence of branching, and although they may well represent *Chondrites*, if no evidence of branching is observed they must be classified as *Planolites*. Burrow diameter ranges from 1 millimeter to 1 centimeter, but averages a few millimeters. At the Ceylon Pool, discrete burrows are not always distinguishable in the mudstone. Rather, the rock has a completely bioturbated nature. These zones also contain *Palaeophycus*, which are not noted anywhere in Facies 8 at Midale and Tyvan. These lined burrows may in fact represent a later tier of burrows than the deposit feeding burrows but there are no well-preserved crosscutting relationships to establish this with any certainty. Locally, facies 8 contains well-preserved (articulated and minimally fragmented) trilobites, ostracods and brachiopods. Facies 8 also contains calcareous, dolomitic and siliceous diagenetic nodules, which may or may not be displacive.

This facies is present as thin interbeds sometimes between the carbonate kukersite-cycles, but a notably thick (1–2 meter) interval can be found approximately 7 meters below the top of the Yeoman Formation in both Tyvan and Midale (Figure 4.1– 4.3). This facies is also found ~8 meters below the top of the Yeoman Formation at Ceylon, but without an examination of the wells located between the studied oil pools, the correlatability can not be confirmed. Furthermore, this facies is repeatedly observed at the Ceylon oil pool (Figure 4.7).

Facies 9. Stylo-Mottled Mudstone

The sediments above the uppermost kukersite in the Midale and Tyvan pools appear on first inspection to greatly resemble the carbonate-kukersite cycles (Facies 2, 5, and 6). Upon closer inspection, enough differences exist to suggest that these sediments comprise a different facies in those two pools. The stylo-mottled facies appears to be absent from the Ceylon pool in the Husky Ceylon 11/5-8-6-19W2/0 well, which is cored in the uppermost Yeoman interval, where this facies lies (Figure 4.7). The mottles are bound by stylolites and this stylo-mottled appearance, which is not observed in any of the other facies, sets this one apart. Although the stylo-mottled nature is a diagenetic fabric, it is the most conspicuous fabric of this facies. Since it occurs only in this facies, some indeterminable sedimentary characteristic may cause this.

The sediments of facies 9 are poorer in allochems and organic matter than Facies 2, 5 and 6 (Figure 4.16). Allochems comprise unidentifiable skeletal fragments, tabulate and rugose corals, gastropods and abundant ostracods. Most of the allochems are less than 1 millimeter in size; however, some floatstone zones appear where allochems are better preserved and are up to 2 centimeters. Facies 9 is dominated by mudstone, but some zones appear to represent former wackstones and packstones. Even in wells where the sediments of this facies are not dolomitized, the allochems are poorly preserved, commonly as molds only.

Kukersitic organic matter are preserved as burrow linings and fill (Figure 2.3, 2.4, 3.8b), but the abundance of organic matter decreases upwards to the top of the Yeoman Formation. Trace fossils exhibit

fluctuating and complex patterns. *Palaeophycus* and *Planolites* occur throughout these sediments. Some zones are riddled with *Asterosoma*, *Phycodes* and *Rhizocorallium*, which are commonly part of composite burrow systems. The matrix in some intervals greatly resembles the *Planolites* mudstone facies, but the presence of these composite burrow systems sets it apart from facies 8. At the Berkley et al. Midale 31/11-35-6-11W2/A, *Rhizocorallium* are most abundant (Figure 3.1). At the Midale pool, there is an overall increase in the abundance of *Rhizocorallium* upward.

Other than factors mentioned in the discussion of trace fossils, another factor, that makes identification and classification of trace fossils in this zone complicated, is the fact that the burrowed intervals are generally bounded by stylolites and solution seams. The regularity of these mottles suggests that they may represent *Thalassinoides*, with secondary deposit-feeding burrows; however, no evidence of this could be found due to extensive stylolite formation. Diagenetically this zone is prone to silicification, with the growth of silicified burrow haloes and chert nodules.

Facies 10. Peloidal Grainstones and Boundstones

The distinction that sets facies 10 apart from the other Yeoman Formation facies, is the absence of the characteristic burrow-mottling of the Yeoman Formation (Figure 4.17). Since the mottles in the uppermost Yeoman Facies become more and more horizontal, the lower contact of this facies may be sharp or gradational with the underlying facies. Where the underlying facies remained undolomitized, the change to dolomite lithology aids in the recognition in both core and well logs (Figure 3.1, 4.1 – 4.4). If no lithologic contrast is present, an arbitrary point, where the mottles lose their vertical aspect, is chosen as the top of the Yeoman Formation.

This facies is most variable in thickness ranging from 1.5 to 6 meters. Lower and upper contacts are both gradational. These sediments are completely dolomitized, but also contain some secondary anhydrite and chert. At Midale and Tyvan, the fabric is commonly grainstone or packstone, or indicative of precursor grainstones, composed of different types of allochems than are common in the Yeoman Formation. Locally, this facies contains boundstones rich in bryozoans. Allochems consist of peloids, gastropods, brachiopods, and more abundant bryozoans than the Yeoman sediments (Figure 4.18a). The relative proportion of these allochems varies from well to well. Lithoclasts and algal mat debris is also noted in some wells. At Ceylon, these sediments may consist of dolomitic mudstones, which lack the diversity of allochems in the other two oil pools.

Many skeletal fragments and allochems are dissolved leading to abundant dissolution porosity. This is thus the most productive zone of the Yeoman-Herald interval in southeastern Saskatchewan. Some grainstone lenses occur with larger allochems and lithoclasts, suggesting storm deposition and higher energy environments. *Planolites* locally occur in great abundance at the base of this interval. They generally become fewer in abundance and less recognizable upward. Cemented hardgrounds, bored by *Trypanites*, are observed at Tyvan.

The variable composition of allochems and sedimentary structures observed in this interval throughout the examined cores is consistent with observations in other studies (Kent and Haidl, 1999; Kendall, 1976). Since Facies 10 lacks the characteristic burrow mottles of the Yeoman Formation, it fits in better with the Herald Formation sediments. These facies correspond to the Basal Lake Alma Member of the Herald Formation (Kent and Haidl, 1999). Facies 10 represents the transition between the subtidal burrowed carbonates and the laminated dolomudstones of the Herald Formation (Lake Alma Laminated Dolomite Member).

Facies 11. Laminated Dolomudstone

Facies 11 consists of cryptocrystalline to finely crystalline dolomitic mudstone (Figure 4.18b,c). This is easily recognized as subtle kick on the gamma ray log (Figure 4.1 – 4.4). The lower contact can be sharp, but it is generally gradational or interbedded with the sediments facies 10. These sediments are commonly stylo-bedded, with organic matter concentrates at the stylolites and solution seams. Locally, facies 11 contains dewatering structures. This facies corresponds to the Herald Formation, Lake Alma Dolomitic Member (Kendall, 1976), also known as the Red River Laminated 'C' dolomite (Kohm and Louden, 1978). The upper contact of Facies 10 is gradational, and commonly interbedded with the overlying anhydrite.

Facies 12. Nodular Anhydrites

The nodular anhydrites of facies 12 are only cored at the Ceylon and Midale Pools. These anhydrites are nodular, bedded or laminated with dolomitic mudstone (Figure 4.19a,b). This anhydrite bed is generally thicker than 5 meters. The bottom is generally gradational with the facies 11, with an increasing proportion of anhydrite upward. There is an absence of fossils and biogenic sedimentary structure, suggesting that in the examined regions syndepositional conditions were too harsh to sustain significant life. No bird's-eye structures or dessication cracks are observed in the examined cores that would suggest some sub-aerial exposure during anhydrite precipitation. Facies 12 corresponds to the Herald Formation, Lake Alma Anhydrites (Kendall, 1976) or Red River Formation, 'C' Anhydrite (Kohm and Louden, 1978).

4.4 Depositional History of the Yeoman Formation

The lateral continuity (Figure 4.1 – 4.4) of the Yeoman and Herald facies corroborates earlier interpretations that these sediments represent subtidal deposits (Kendall, 1976; Kent and Haidl, 1999). Further evidence for subtidal deposition includes the absence of features indicating subaerial exposure, the absence of meteoric diagenetic fabrics (see Chapter 5), and the fossil and trace fossil assemblages. The thickness of these deposits also supports a subtidal depositional environment. Superficially, Yeoman facies exhibit little variability; one exception being the *Planolites* mudstone, facies 8. However, upon closer examination in the upward succession of facies, a gradual change in organic matter and sedimentary fabrics

is observed, which indicate that the Yeoman sea was gradually becoming more restricted. Subtle variations in allochems, allochem-to-mud ratios, biogenic sedimentary structures and the abundance of organic matter indicate that the palaeoecological factors varied enough to alter the life in the sea. Some of the variability is due to taphonomic variations, but where the same variability is consistent in similar facies having undergone different diagenetic alteration, one can infer the differences to be due to changes in depositional environment.

Taphonomic changes, which skew the availability of skeletal fragments remaining and preserved in the sediment can also be useful in deciphering the palaeoenvironmental conditions (Speyer and Brett, 1988). This is particularly valuable in the examined facies, where the makeup of allochems throughout the facies shows only subtle variations. They are dominated by echinoderm fragments, and fragments of multi-element skeletons (such as trilobites and brachiopods) which are poor indicators of water energy within the Yeoman Formation since they fall apart soon after the death of the organisms. Arborescent allochems, such as bryozoans, and multi-element skeletons are sensitive to fragmentation, and thus can be key taphonomic indicators of changes in current energy among facies in which they occur (Brett and Baird, 1986). All of this places added value on the trace fossils in determining what sedimentary and palaeoenvironmental changes occurred during deposition of the Yeoman Formation. Furthermore, biogenic sedimentary structures are often good indicators of shifts in the behaviour of benthic organisms, which in turn are sensitive to changes in palaeoenvironmental conditions such as bottom water oxygenation, water circulation, illumination, salinity and substrate consistency.

The lowermost Yeoman sediments, facies 1, are penetrated in a few cores, but it is inferred from the uniform downward signature of the well logs (Figure 4.5 – 4.7) that the sediments are relatively uniform downward to the base, until they become more argillaceous (Kendall, 1976). The mudstones of facies 1 are believed to represent a lower ramp environment, where water energy is low and carbonate accumulation is slow. Allochems are dominated by echinoderm debris, which are fragmented and disarticulated. This, in itself, is not necessarily indicative of constant reworking of the sediments, since studies of modern echinoderms and arthropods indicated that these skeletons are disarticulated within hours or days after death of these organisms (Meyer and Meyer, 1986). However, the lack of bedding features and other sedimentary structures does indicate that these sediments are significantly reworked. There are two hypotheses to explain the almost monospecific suite of trace fossils. The *Planolites* either represent the last tier of burrows, having obliterated all the earlier suites, or alternatively the activities of deposit-feeding infauna made the sea-floor difficult for the establishment other feeding mechanisms. Commonly, bioturbating infauna resuspend abundant detritus that limits the feeding of low-level deposit feeders. Their activities also increase the water content of the substrate, making the sediment too soft (thixotropic) for the establishment of more complex burrow types (Rhoads, 1970).

It is believed that these sediments represent below fair weather wave base deposits, since there is an absence of wave sedimentary structures. A low energy shelf environment is indicated by the muddy nature of sediments, and also by the abundant traces of deposit-feeding organisms. The most conspicuous

biogenic sedimentary structures of this zone, are the *Trichophycus*, which are filled with sediment unlike the host matrix. Their contrasting fill, which contains more fragile and better preserved allochems, is believed to more closely resemble the original faunal makeup, and these sheltered burrow environments allowed the preservation of less robust allochems, such as bryozoans and trilobites. Their fill is also richer in organic matter. Furthermore, since water energy was too low for filter-feeding infauna to colonize the substrate, bioturbation seems to be the greatest factor for the breakdown of carbonate sediment. Facies 1 is dominated by *Planolites*, and locally *Chondrites,* which indicate favoured deposit-feeding.

Facies 2, comprising packstones and wackstones, indicates a slightly higher energy environment than that of Facies 1. The lower mud content of these sediments suggests better water circulation. The fine sediment would have been winnowed by currents. Wave and tidal sedimentary structures are not observed; therefore, bottom currents and storms were probably the main hydraulic forces circulating the bottom waters. This facies may also have had a higher sedimentation rate thus preventing the extensive reworking and breakdown of allochems. The preservation of allochems is better at the Tyvan pool, than at Midale and Ceylon pool, partially a result of matrix dolomitization. Grainstone beds, indicative of storm activity, are rare to absent but this is expected in a platform carbonate environment where event beds are easily destroyed by daily reworking.

The gradual change to Facies 2, especially the decrease in mud content and the presence of *Palaeophycus* and *Skolithos*, which are filter-feeding burrows, is indicative of an increase in water circulation. These sediments most closely resemble those of the Tyndall Limestone, however they lack the large macrofauna, which are so well known from the Tyndall Limestone sediments. This was observed by others as well (Kendall, 1976, 1977; Kent and Haidl, 1999). Kendall (1977) suggested that restriction of the seaway in southeastern Saskatchewan inhibited the growth of such large macrofauna. Such organisms tend to colonize environments where enough nutrients are circulated in the water, yet the water is clear enough for their siphons not to be clogged. These dwelling burrows (domichnia) dominate this facies. In the modern, dwelling burrows are generally limited to well-illuminated sea-floor environments, where their primary purpose is protection from predation (Schäfer, 1972). Similar to Facies 1, the allochems present are dominated by more robust forms, suggesting that the less robust ones were fragmented and broken down by the water energy or bioturbation. *Trichophycus* have the same fill as in Facies 1, supporting the view that their fill represents the original makeup of these sediments at the sea-floor, since it is unlikely that these 'identical' beds would always be removed, with evidence of their existence only being preserved as hidden bedding contacts.

Since the burrows and their dolomite haloes exhibit little mechanical compaction, these were both most likely formed after some lithification and dewatering. This may also suggest that only the last tier of burrows were preserved. The fact that these sediments are rich in skeletal fabrics also makes the less susceptible to mechanical compaction.

A gradual palaeoenvironmental change is recorded by the deposition of Facies 3 at the Tyvan and Midale pools. This transition is much sharper at Ceylon. The type of organic matter shifted to *G. prisca*

alginite, and this indicates an there was increasing abundance of this maceral in the water column. An increase in thickness of the burrow lining and change in type of organic matter suggest that the water chemistry also changed, and these correspond to the inferred onset of the earliest *G. prisca* algal bloom, stages 2 and 3 of the carbonate-kukersite cycles. There is also a decrease in burrow abundance. The burrows also have more vertical components, which may suggest a preference for suspension-feeding behaviour or more rapid sedimentation rates. The latter interpretation is also supported by the increase in abundance of well-preserved gastropods in this interval.

The shift in environmental parameter that occurred at this time caused the matrix to become more resistant to dolomitization at both Tyvan and Midale; thus, this zone can easily be picked off the well logs (Figure 4.1 – 4.3). At Tyvan this facies is not as distinctly different on well logs from facies 2, because the matrix in Facies 2 remained undolomitized at Tyvan. The burrow mottles, characteristic of the Yeoman sediments, are still present, but their diameter is generally smaller and they commonly occur in a lower density. These sediments likely underwent some earlier cementation, but no evidence of different diagenetic fabrics is found (Chapter 5) to suggest why these sediments remained undolomitized.

Above facies 3, the carbonate-kukersite cycles represent periodic algal blooms of *Gloeocapsomorpha prisca*, which are discussed in chapter 3. The upper Yeoman Formation (Red River 'C' Burrowed Member) contains kukersite beds throughout the Williston Basin (Kendall, 1976). Carbonate intervals between the kukersites represent periods where sedimentation returned to relatively normal, pre-kukersite time. Depending on various factors these facies 5, 6, 7 and 9 differ from Facies 1 and 2 to various degrees. The presence of common firmgrounds and hardgrounds in Lower Paleozoic sediments has been noted by many (Palmer, 1978; Brett and Brookfield, 1984). Those formed at the base of kukersites are interpreted to have formed during times of sediment by-passing. A bored cemented surface is evidence of sedimentary omission (Bromley, 1975). Reburrowing of their fill commonly occurs when organisms find the sea floor too hard to penetrate.

Facies 5, is preserved as nodular- or blurry-mottled limestones and dolomites, represent periods of lower water energy, with presumed extensive reworking of the sediment. This is indicated by the predominantly mudstone fabric of these sediments. The large burrow systems, *Planolites* and *Thalassinoides*, are interpreted as large deposit-feeding networks. This is supported by the dominantly horizontal nature of these burrows and abundant organic matter in these sediments. No evidence of suspension of feeding activities is observed, suggesting that water energy was low, perhaps indicating that there was a deepening event. Storm activities were recorded by occasional grainstone and packstone lenses preserved within this facies. Generally, facies 5 has gradational both upper and lower contacts, suggesting gradual water deepening and shallowing.

Facies 2 dominates the carbonates between the kukersite cycles, corresponding to stage 1 of the carbonate-kukersite cycles when the water column has a relatively diverse planktonic fauna. Since it generally occurs right above the kukersites, these were probably deposited when *G. prisca* algal blooms died out and deposition most-closely resembled pre-kukersite deposition. This is not only indicated by the

low amount of *Gloeocapsomorpha prisca* (disseminated A maceral) in burrow linings, but also the return of other types of macerals and zooplankton. The allochems here exhibit the greatest variety. The ichnology, dominated by filter-feeding behaviour *Palaeophycus* and *Skolithos,* suggests more water circulation than during kukersite deposition.

Facies 6 generally represents the early onset of *G. prisca* algal blooms, stage B of the carbonate-kukersite cycles. At this point, *G. prisca* was beginning to dominate the organic matter in burrow linings, and presumably was thus more abundant in the water column. The conditions appear to be an intermediate between those during the deposition of Facies 2 and 5. The matrix sediments are very similar to those of Facies 2, indicating that there was an active carbonate factory supplying the carbonate sediment. On the other hand, the burrows indicate more restricted conditions. The various complex burrows and burrow systems suggest that the infauna had to resort to more complex feeding and waste storage behaviours. One has to keep in mind that the preserved burrows may in fact be the over-printing of a previous trace fossil assemblages, and these complex burrows represent the deepest feeding tier; however, these burrow networks appear to have been continually reworked, since the burrow diameter remains constant. The conditions were clear enough for the calcareous allochems, such as bryozoans, trilobites and corals to grow. Adverse sea-floor conditions due to the high concentration of *Gloeocapsomorpha prisca* in the water column resulted in the complex infaunal habits. Since the horizontal view of the burrow systems is restricted, it is impossible to tell if the *Rhizocorallium* are deposit or filter-feeding types of Fürsich (1974a). One can infer that since *G. prisca* is absent from the matrix and fills of deposit feeding burrows, the macerals were introduced into the burrow networks by the infauna. *Asterosoma* and composite burrow systems indicate continual reworking of these burrow systems for nutrients, presumably at times when food was less available at the sea-floor and in the water column. Periods of increased salinity, indicated by the halite hoppers, may have been responsible for adverse conditions. *Planolites* and *Chondrites* are the last tier of burrows, which indicate reworking of the networks for a food source, presumbly because they commonly have comparable diameters to earlier burrows. Where the diameter remains consistent, it may easily represent a shift in feeding patterns of the same species (D'Andrea and Lopez, 1997). These complex burrow systems in the carbonate sediment between the kukersite indicate that the environment was undergoing palaeoecological changes that forced the benthic and perhaps planktonic fauna to change feeding strategies.

Facies 7 of the carbonate-kukersite cycles at Tyvan and Midale, are slightly different. Much of this may be due to diagenetic overprinting that causes these sediments to become so vuggy. Either this zone is deposited as packstones and wackstones, suggesting that at the time of deposition, water energy was high enough to winnow out the muds. One grainstone lense can be correlated across the entire Midale pool, and with some uncertainty, it may correspond to the grainstone lens in the Tyvan pool wells, suggesting the existence of storms which blanketed extensive areas with coarse skeletal debris.

The cyclical carbonate-kukersite zone also contains some intervals of Facies 8. This is especially noted in the Ceylon pool where several burrowed mudstone intervals occur between kukersite beds (Figure

4.7). The muddy nature of sediments in Facies 8, and exclusive trace fossil assemblage of deposit feeding burrows, suggests that these sediments were deposited during periods of quiescence, perhaps brought on by a water deepening. Their correlatability over extensive areas supports the interpretation that they are flooding surfaces. Peculiar early diagenetic nodules, which displaced laminae, formed before lithification of the sediment at Tyvan and Midale. These nodules may be calcareous, dolomitic or siliceous, and any of the above can be found in this facies, whether the sediments are dolomitized or not. These are indicative anoxic sea-floor conditions that may result from a flooding event.

The upper contact of facies 8 is marked by kukersite deposition, which grades into facies 6. At Tyvan and Midale one more *G. prisca* algal bloom is recorded before the deposition of facies 9. Facies 9 is not observed at Ceylon, where facies 6 graded into the Herald Formation (facies 10). The common early diagenetic fabrics in Facies 9 indicate deposition during restricted water circulation, compared to the deposition of the facies below. First, the abundance of silica precipitation in this zone both at Tyvan and Midale, notably that silica is only found in this zone. The silica/chert nodules appear to be early diagenetic, especially where they form around burrows. Zijlstra (1987) noted that silica concretions in Maastrichtian chalks were precipitated at the boundary between the oxidizing and reducing sediment, suggesting that these burrows may have remained at that boundary long enough for these nodules to form. Furthermore, the growth of silica nodules, some as large as 10 centimeters, indicates that there was an increased silica source in the water column. Secondly, composite deposit feeding burrows dominate the trace fossil suite of Facies 9, also indicating that each zone of the sediment was repeatedly reworked. Lowered oxygen and water circulation would have caused organisms to shift their feeding behaviour.

Finally, this facies contains well preserved storm beds with large, well preserved gastropods, brachiopods, trilobites and ostracods. These storm beds, being better preserved than in the lower Yeoman (facies 1 through 7), indicate that perhaps the day to day reworking of sediments was not as great as prior to the carbonate-kukersite cycles. The above observed properties suggest that water circulation never returned to the ambient, open marine as during deposition of facies 1 and 2. At the top of the Yeoman Formation in the Ceylon pool, the sediments are more commonly mudstones, and the kukersite cycles interval persist up to the deposition of the Herald Formation (facies 10). The matrix of these sediments also is more extensively dolomitized, perhaps due to the fact that muddier sediments are more susceptible to dolomitization (Murray and Lucia, 1967).

There is a subtle relationship between the abundance of *G. prisca* alginite and the preservation of allochems, which should be more closely examined. Allochems exhibit a greater variety, and better preservation in the carbonate-kukersite cycles. This appears to be independent of dolomitization, and hence the presence of *G. prisca* in the water column may have also impeded the activities of benthic fauna, thus reducing the extent of the breakdown of allochems. If indeed *G. prisca* was a slightly toxic algal bloom, many of the sea-floor fauna may have suffered. This relationship is notable, but a more detailed examination of fragmentation and biota is required to test this hypothesis.

Although the Herald Formation is not the focus of this study, the description is necessary to justify separating Facies 10, 11 and 12 from the Yeoman Formation. Within facies 10, there are great differences observed in between wells, but this author sees no evidence contradicting the earlier interpretation of Kendall (1976) and Kent and Kissling (1998) that these sediments suggest a shallowing episode to above fair-weather wave base. The mudstone nature of this facies at Ceylon may indicate that water shallowing was not as notable in that area. Dewatering structures, observed in all three oil pools, suggest some episodes of rapid sedimentation. Facies 10 is extensively dolomitized in all the examined wells, but sedimentary fabrics are still relatively well preserved, and no indication of subaerial exposure is observed. The ichnological diversity of these sediments is poor, and limited to *Planolites* at the base of this zone. Locally *Trypanites* are found on hardground surfaces. Allochems are different, generally having more abundant gastropods, bryozoans and peloids than the Yeoman facies.

The dolomite mudstones of Facies 11 indicate that conditions became evaporitic during their deposition. No evidence of subaerial exposure is observed, and this is consistent with the findings of Kent and Haidl (1999) and Kendall (1976). These sediments bear no resemblance to intertidal and supratidal sabkha dolomites, because they lack structures characteristic of intertidal deposition such as mudcracks, fenestral structures and dissolution breccias (Shinn, 1983; Warren, 1991). Other than a few ostracods, no allochems are found in this dolomite. The presence of ostracods is used by Derby and Kilpatrick (1985) as indicators of a restricted environment. Where the contact is cored, the contact between Facies 11 and 12 was gradational. The dolomite and overlying anhydrites are interbedded, with gradually increasing amount of anhydrite. This contact is also easily recognizable on well logs.

The anhydrites of facies 12 are believed to represent primary evaporites precipitated subaqueously. Much like the laminated dolomudstone (facies 11), these evaporites lack evidence of subaerial exposure, such as bird's eye structures and dessication cracks, suggesting that these are precipitated subaqueously. Furthermore, evaporite beds thicker than 1 m, which are laminated or bedded, and relatively pure in mineralogy commonly represent subaqueous evaporite deposits (Warren, 1991).

4.5 Conclusions

In the examined core, twelve different facies are observed, with nine belonging to the Yeoman Formation. Similar upwards facies successions are found in all three oil pools. The trace fossil assemblages support previous interpretations that the carbonate-evaporite cycles, represented by the Yeoman and Lower Herald Formations (Red River 'C' Member), indicate increased restriction upwards, but deposition within a subtidal carbonate platform. With the gradual deposition of the Yeoman Formation, the burrows gradually shift to indicate more restricted sea-floor conditions. The cyclical algal blooms of *Gloeocapsomorpha prisca*, which resulted in the deposition of carbonate-kukersite cycles, greatly affected the activities of benthic fauna, as well as carbonate sedimentation. Many organisms, such as corals and echinoderms, live where water energy is sufficient to support their filter-feeding habits. When such organisms die, their decay makes the sea-floor rich in nutrients, hence the sea-floor can sustain deposit-feeders in both high and low

water energy environments. It is believed that restriction of sea-floor fauna reduced reworking of sea-floor sediments in the Yeoman Formation, resulting in better preservation of allochems.

Classical facies models need to be adjusted to be applicable in carbonate sedimentary environments, because sediment production is not only controlled by water energy, but by all the factors affecting the growth of animals with calcareous skeletons. Ichnofacies models for platform carbonates require analysis of the interactions of biota in many such systems and would prove to be a fascinating endeavour.

Figure 4.1

Cross-Section AA' Through the Yeoman Formation: Midale Pool

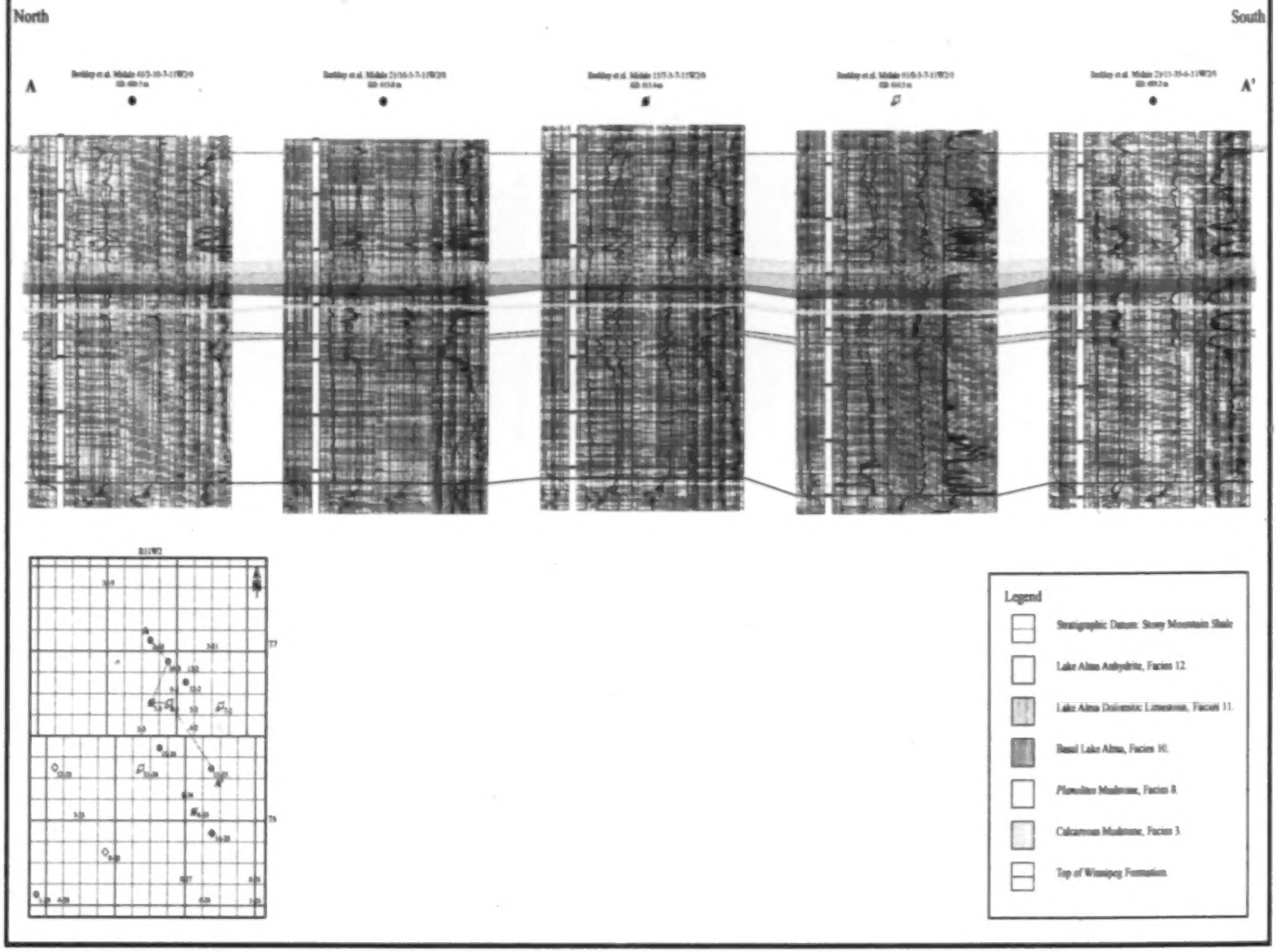


Figure 4.2

Cross-Section BB' Through the Yeoman Formation: Midale Pool

South

North

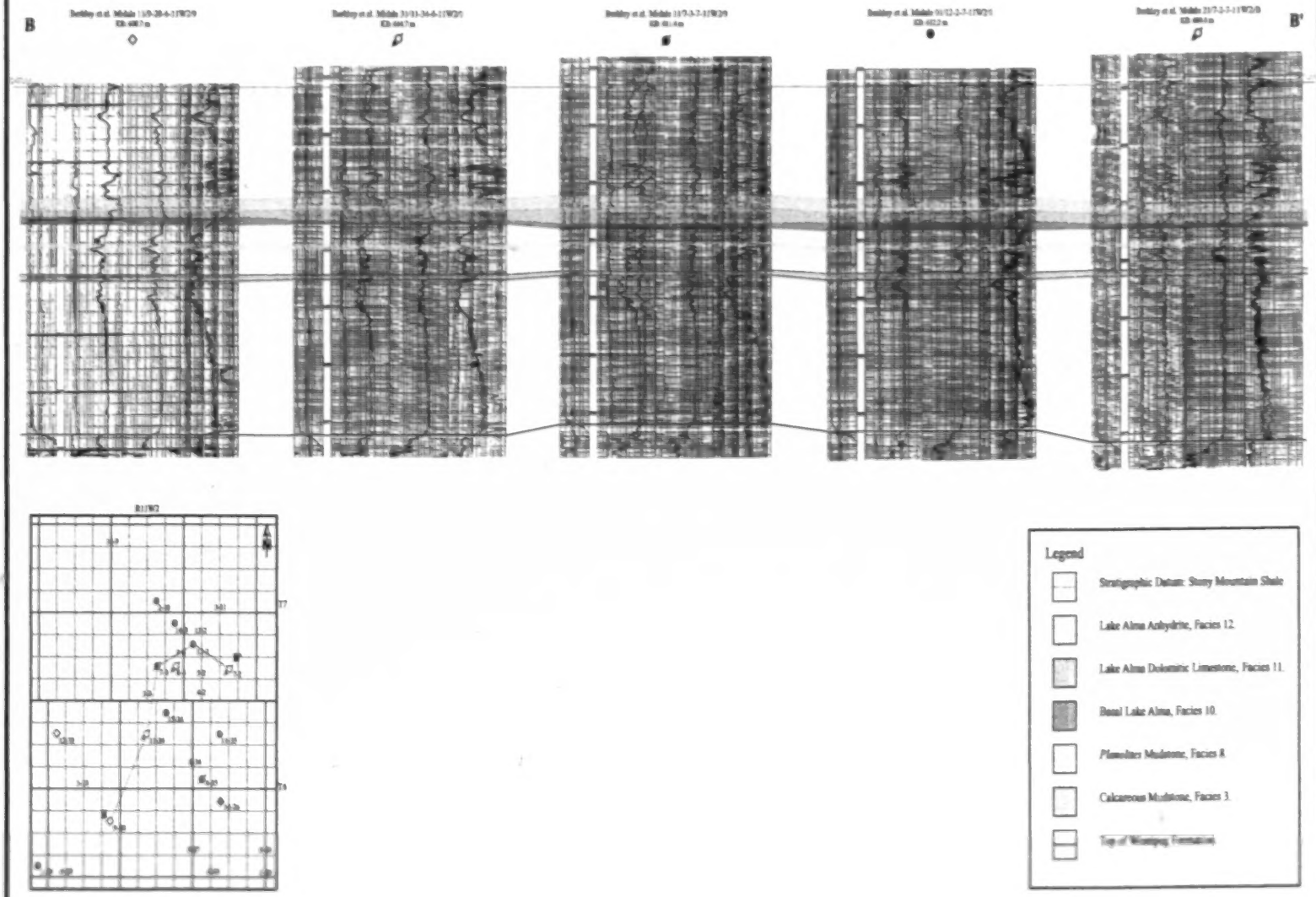


Figure 4.3

Cross-Section AA' Through the Yeoman Formation: Tyvan Pool

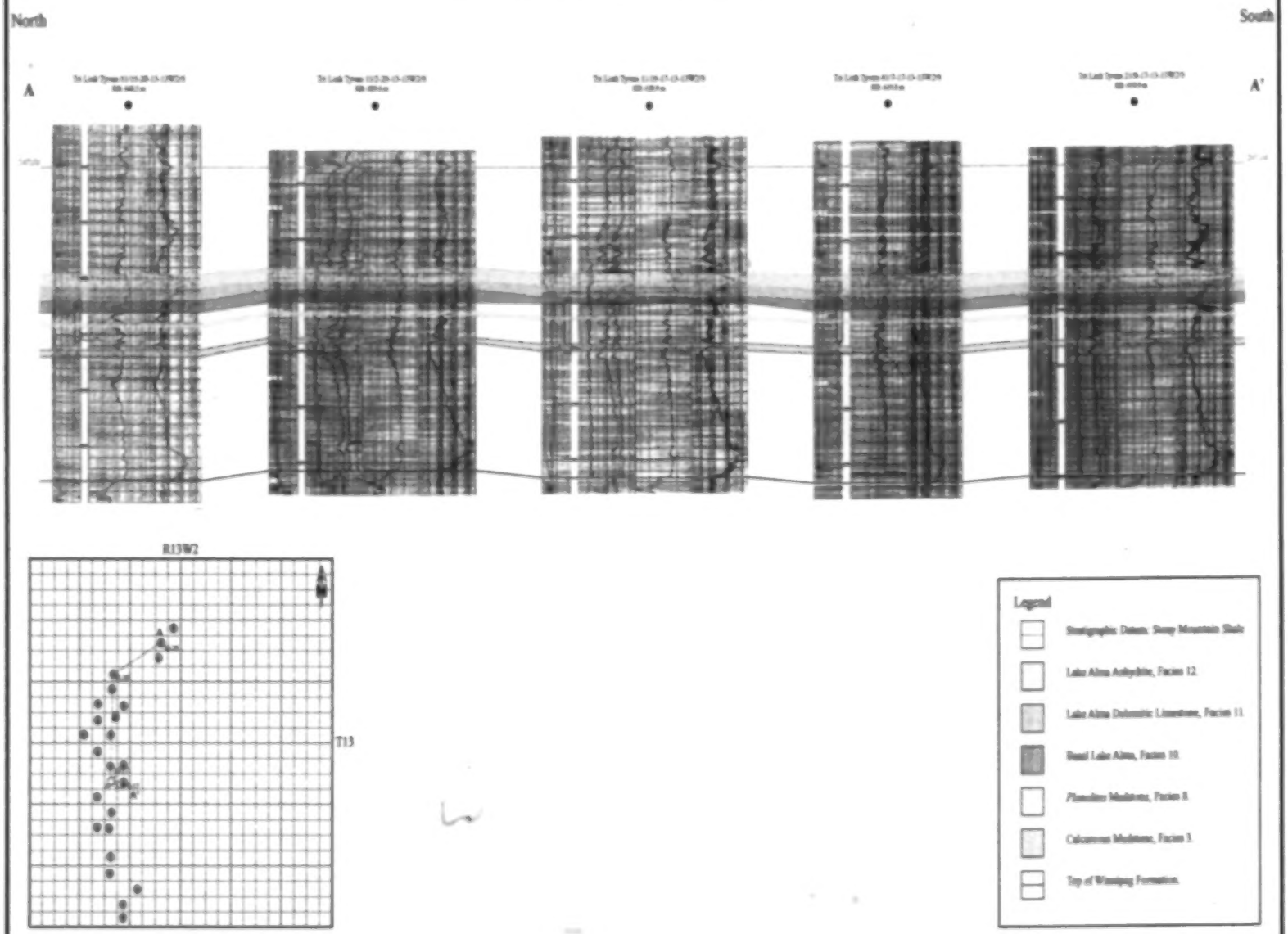


Figure 4.4 Cross-Section AA' Through the Yeoman Formation: Ceylon Pool

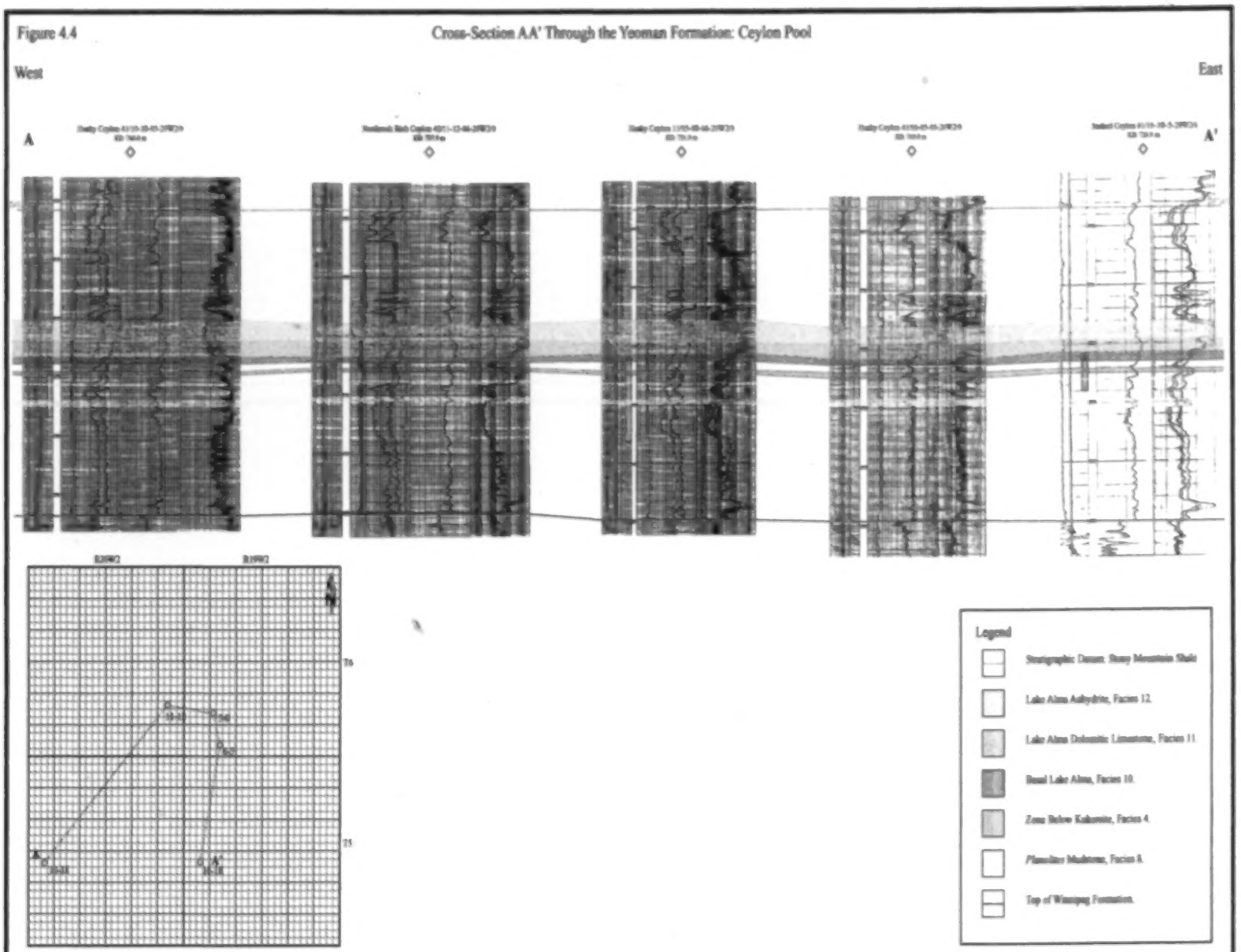


Figure 4.5

Type Log of the Yeoman and Herald Facies at Midale

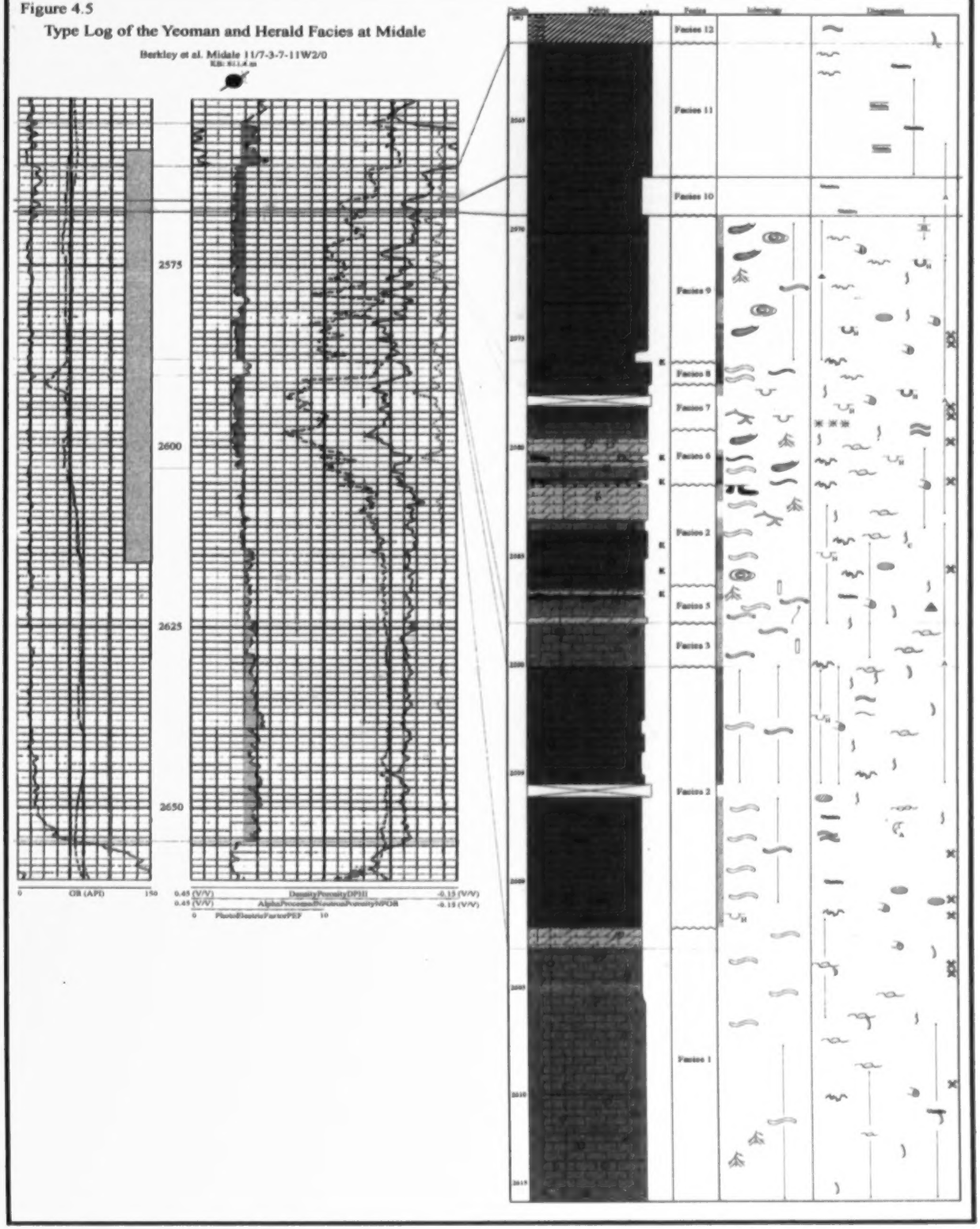


Figure 4.6

Type Log of the Yeoman and Herald Facies at Tyvan

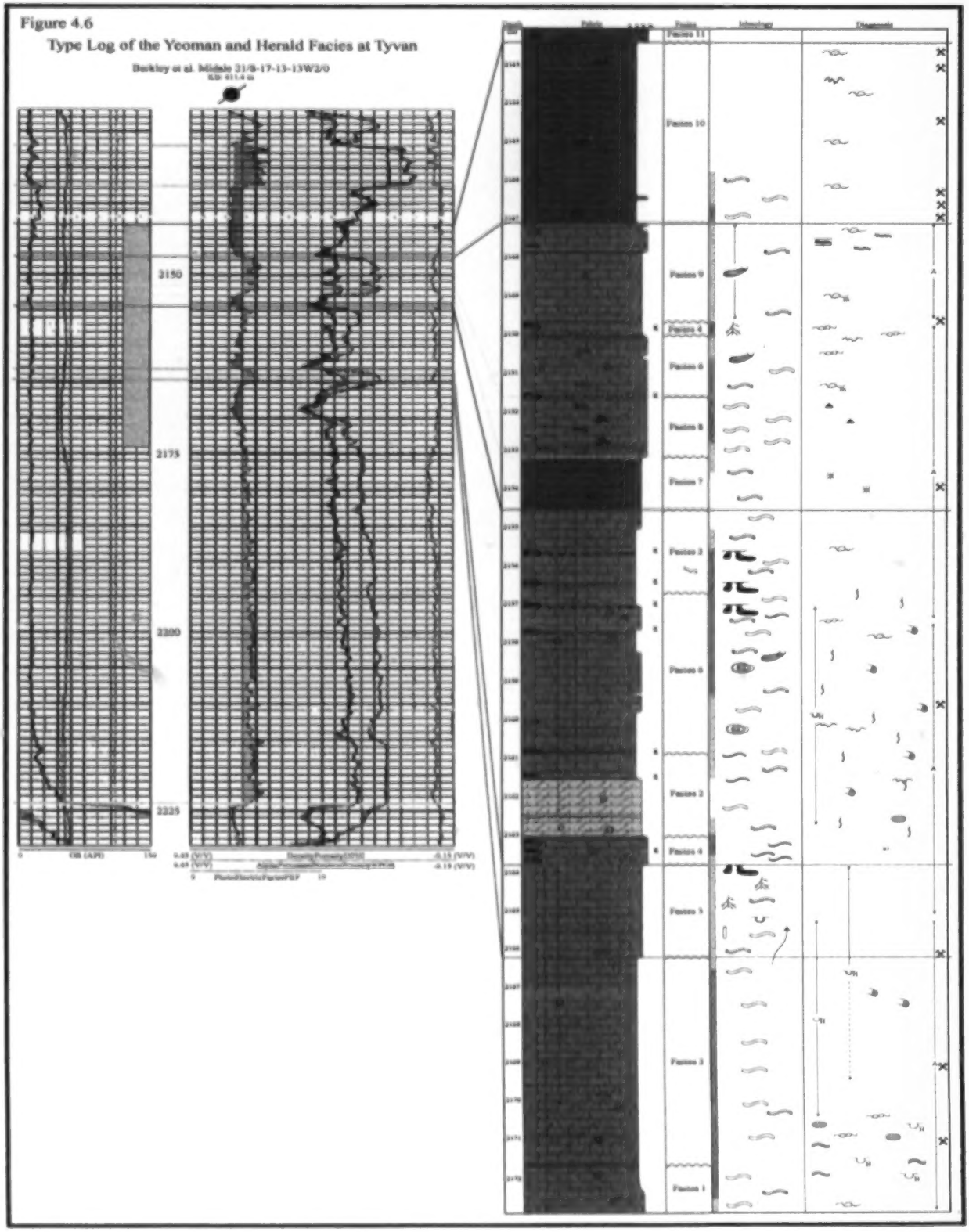


Figure 4.7

Type Log of the Yeoman and Herald Facies at Ceylon

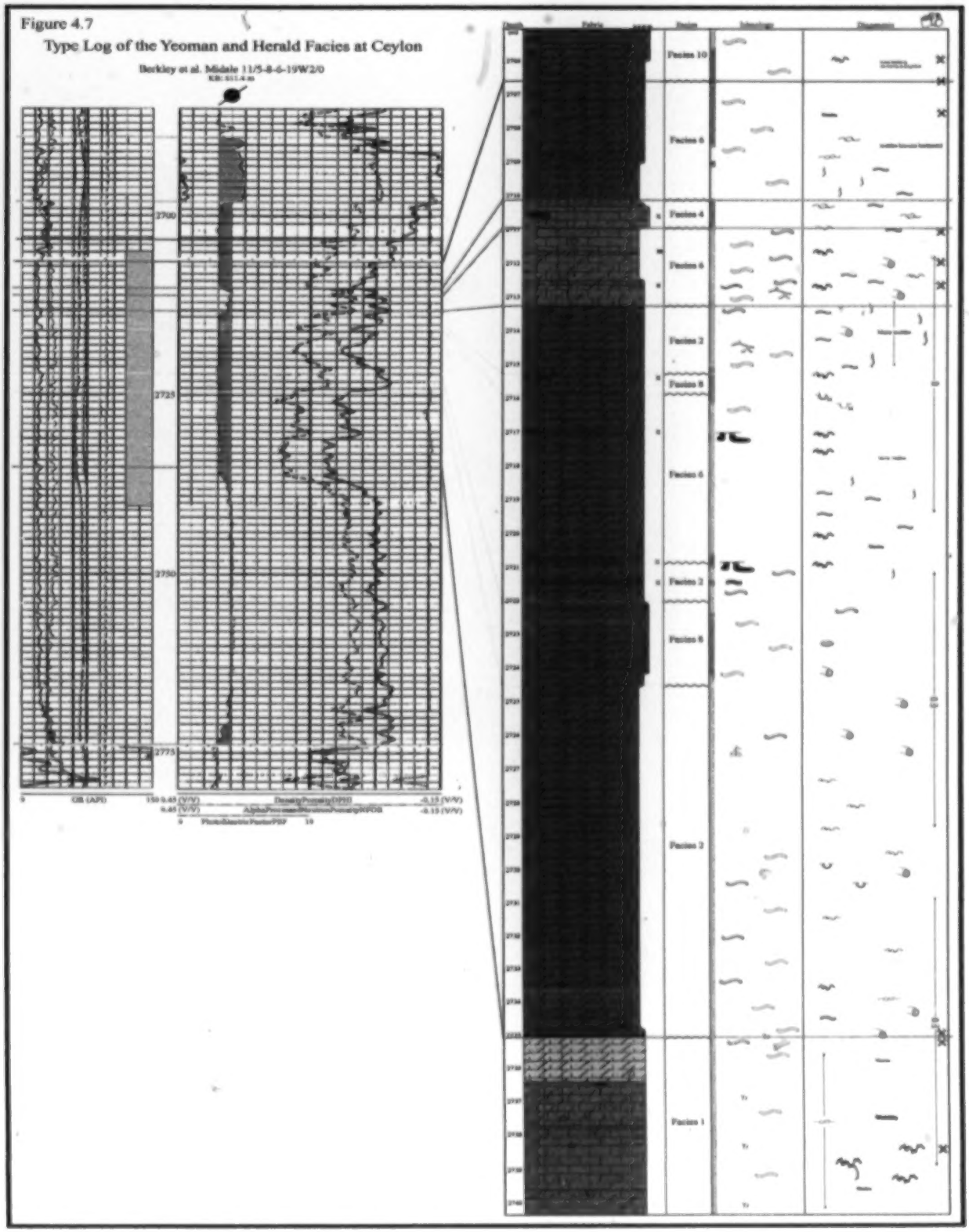
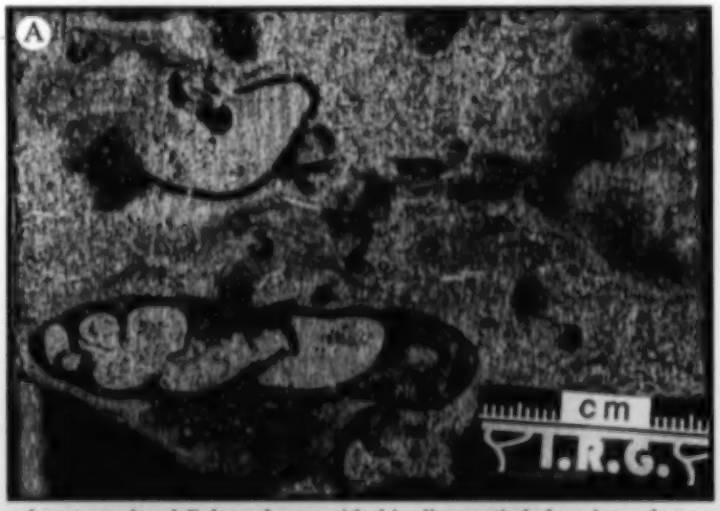


Figure 4.8 Facies 1: Echinoderm-Rich Mudstones and Wackstones

A. Faint *Planolites* and dolomitic mottles.
11/7-3-7-11W2/0, 2614.2 m.
B. Outer surface of the core from a calcareous interval.
41/2-10-7-11W2/0, 2579.4 m.

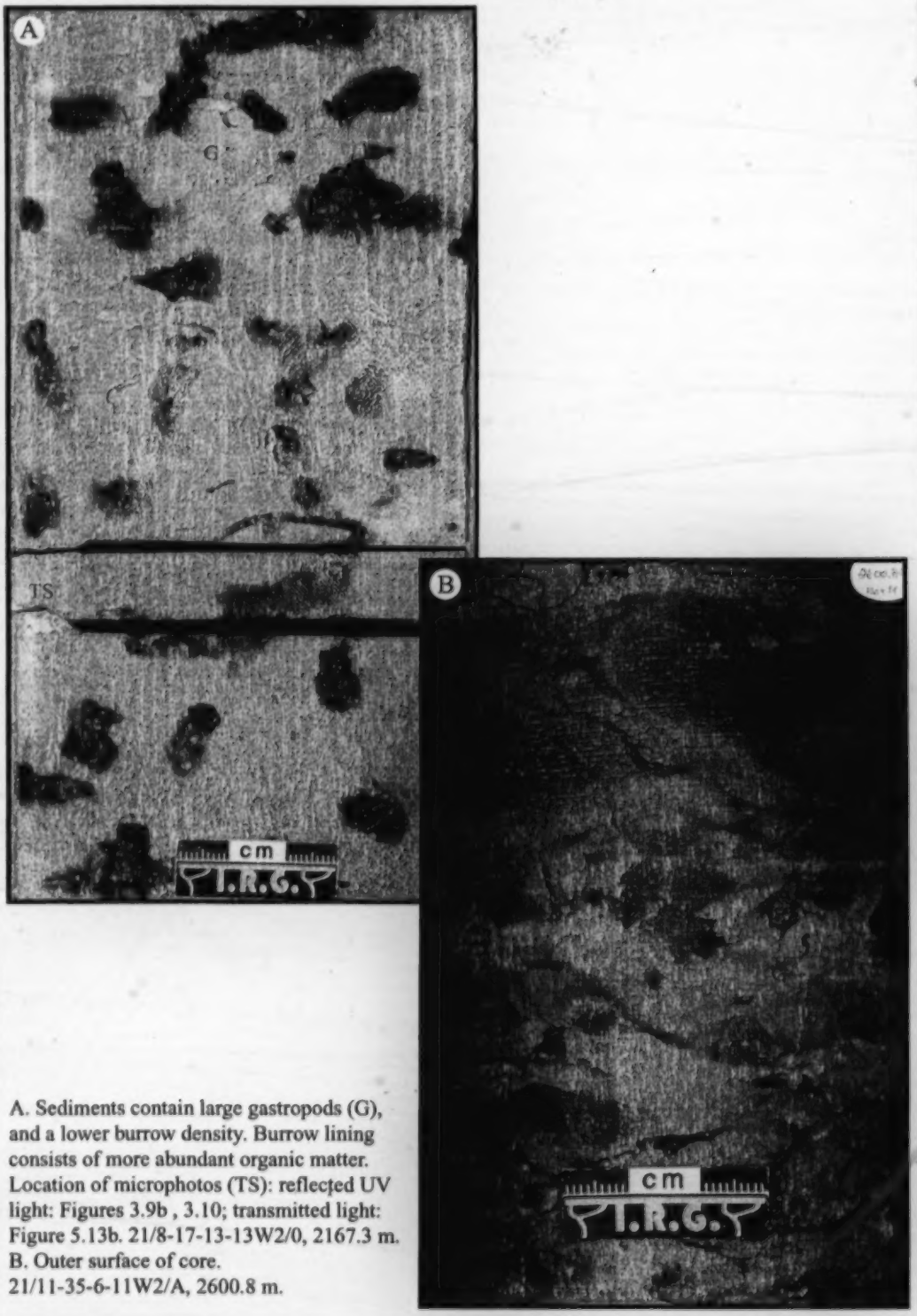
Figure 4.9 Facies 2: Echinoderm-Rich Wackstones and Packstones



A. Bored gastropod and *Palaeophycus* with thin diagenetic haloes in packstone matrix. 21/8-17-13-13W2/0, 2170.9 m.

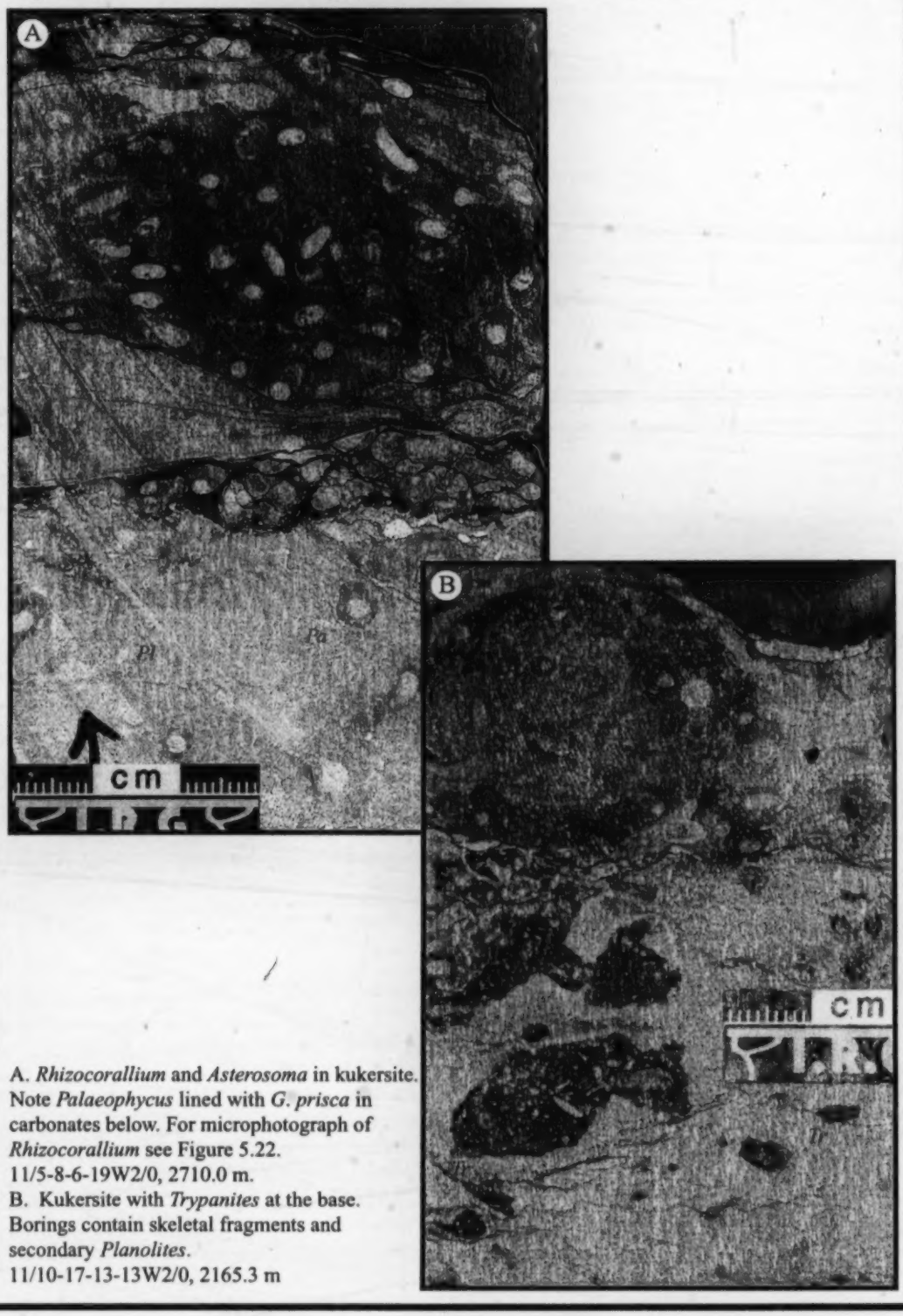
Trace fossils dominated by *Palaeophycus*. Allochems by echinoderm fragments.
B. 21/11-35-6-11W2/A, 2592.4 m. C. 41/2-10-7-11W2/0, 2601.5 m.

Figure 4.10 Facies 3: Calcareous Mudstones



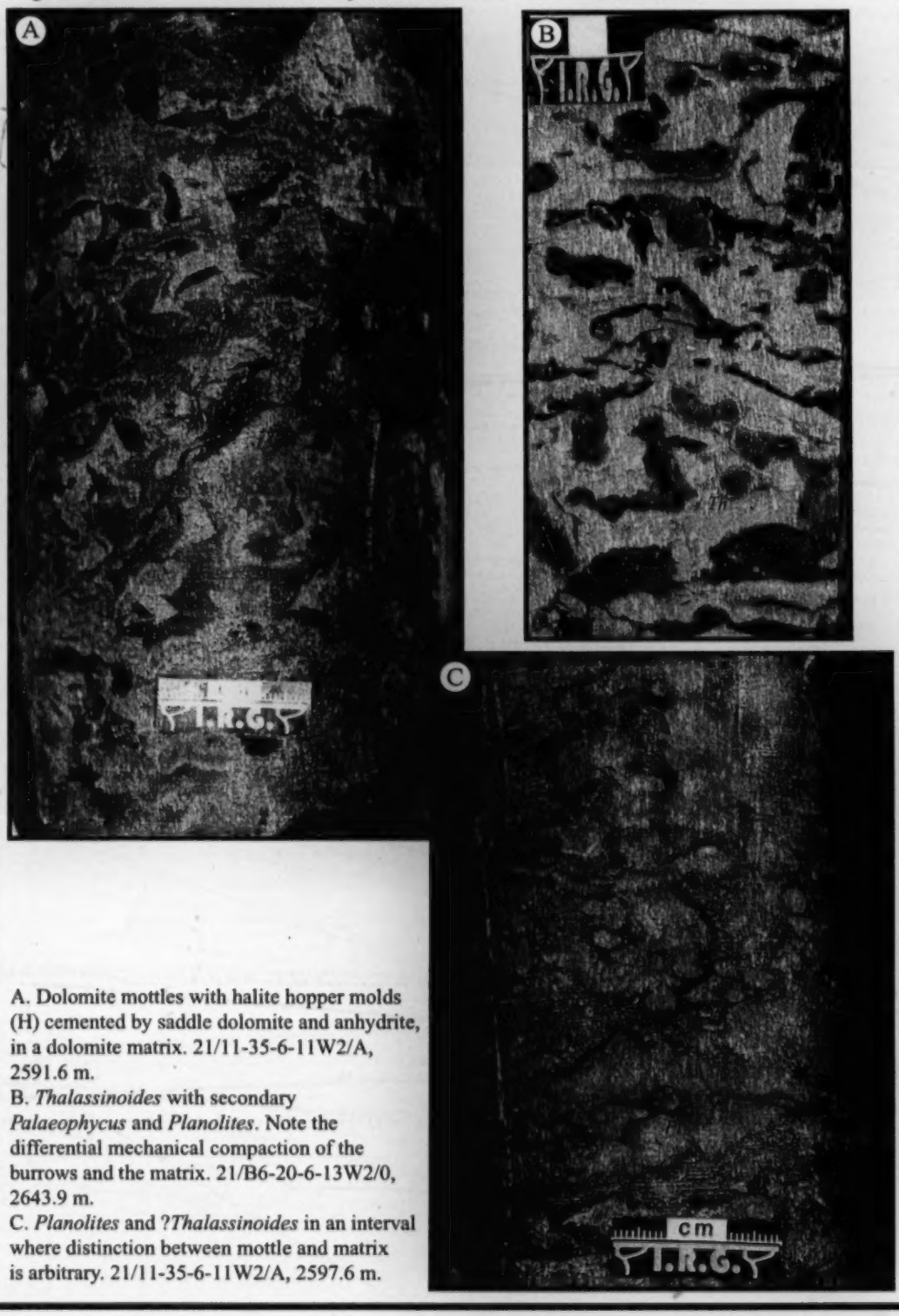
A. Sediments contain large gastropods (G), and a lower burrow density. Burrow lining consists of more abundant organic matter. Location of microphotos (TS): reflected UV light: Figures 3.9b , 3.10; transmitted light: Figure 5.13b. 21/8-17-13-13W2/0, 2167.3 m.
B. Outer surface of core.
21/11-35-6-11W2/A, 2600.8 m.

Figure 4.11 Facies 4: Organic-Rich Mudstones or Kukersites



A. *Rhizocorallium* and *Asterosoma* in kukersite. Note *Palaeophycus* lined with *G. prisca* in carbonates below. For microphotograph of *Rhizocorallium* see Figure 5.22.
11/5-8-6-19W2/0, 2710.0 m.
B. Kukersite with *Trypanites* at the base. Borings contain skeletal fragments and secondary *Planolites*.
11/10-17-13-13W2/0, 2165.3 m

Figure 4.12 Facies 5: Blurry-Mottled and Nodular Mudstones



A. Dolomite mottles with halite hopper molds (H) cemented by saddle dolomite and anhydrite, in a dolomite matrix. 21/11-35-6-11W2/A, 2591.6 m.
B. *Thalassinoides* with secondary *Palaeophycus* and *Planolites*. Note the differential mechanical compaction of the burrows and the matrix. 21/B6-20-6-13W2/0, 2643.9 m.
C. *Planolites* and ?*Thalassinoides* in an interval where distinction between mottle and matrix is arbitrary. 21/11-35-6-11W2/A, 2597.6 m.

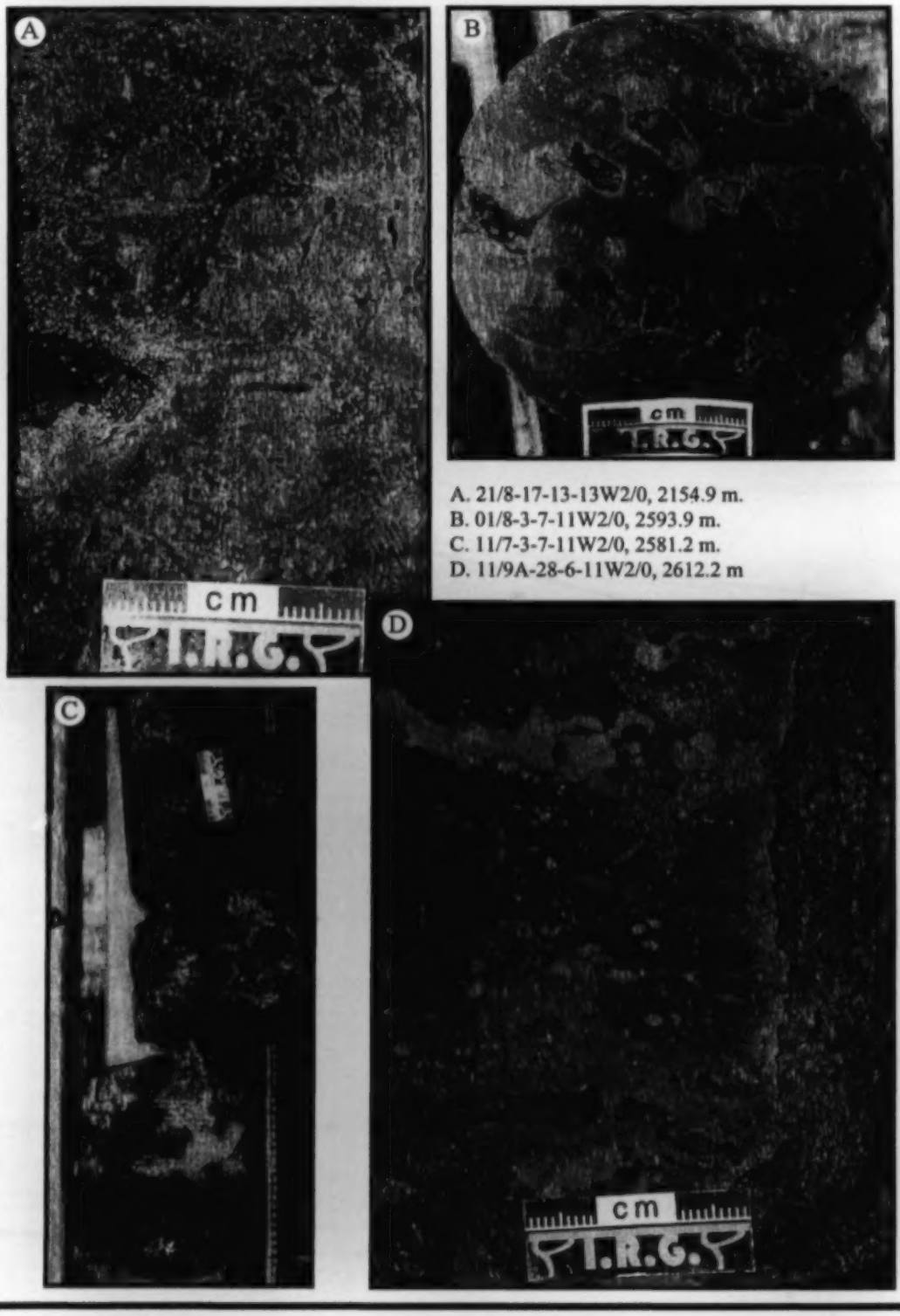
Figure 4.13 Facies 6: Wackstones with Composite Burrow Systems

A. Horizontal section through composite burrow system. 41/6-5-6-19W2/0, 2742.5 m.

B. Re-burrowed *Thalassinoides*.
11/9A-28-6-19W2/0, 2616.0 m.

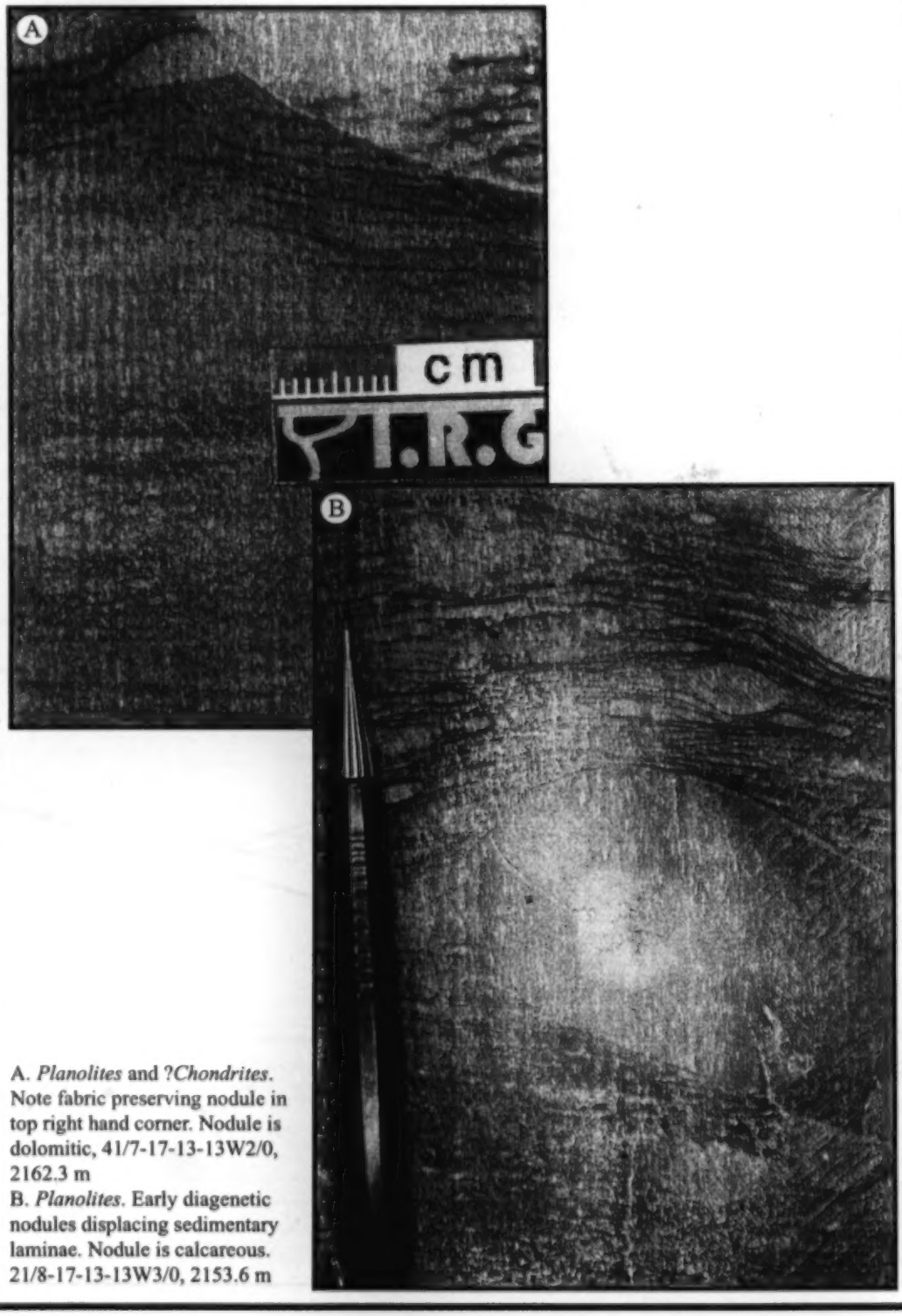
C. Reworked burrows.
11/9A-28-6-19W2/0, 2615.2 m.

Figure 4.14 Facies 7: Vuggy Dolomites



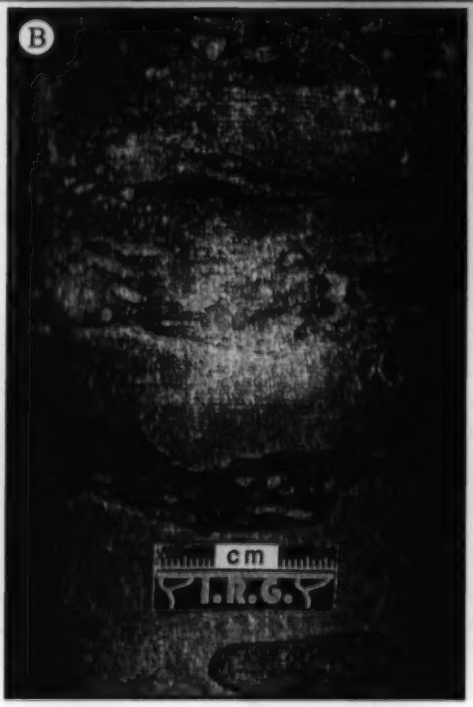
A. 21/8-17-13-13W2/0, 2154.9 m.
B. 01/8-3-7-11W2/0, 2593.9 m.
C. 11/7-3-7-11W2/0, 2581.2 m.
D. 11/9A-28-6-11W2/0, 2612.2 m

Figure 4.15 Facies 8: *Planolites* Mudstone



A. *Planolites* and ?*Chondrites*. Note fabric preserving nodule in top right hand corner. Nodule is dolomitic, 41/7-17-13-13W2/0, 2162.3 m
B. *Planolites*. Early diagenetic nodules displacing sedimentary laminae. Nodule is calcareous. 21/8-17-13-13W3/0, 2153.6 m

Figure 4.16 Facies 9: Stylo-Mottled Mudstones

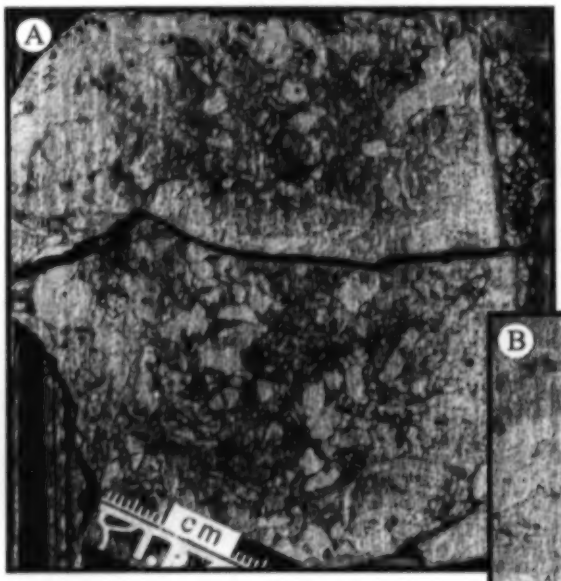


A. *Palaeophycus* have several diagenetic haloes. Locally, the white zone (S) represents silicification of the matrix. 01/8-3-7-11W2/0, 2588.5 m

B. Pressure solution occurring at contacts between visibly burrowed (V) and faintly burrowed (F) sediment. A: anhydtrite nodules. 41/2-10-7-11W2/0, 2572.8 m.

C. Outer core of same zone as B. 41/2-10-7-11W2/0, 2571.2 m.

Figure 4.17 Facies 10: Peloidal Grainstones and Boundstones

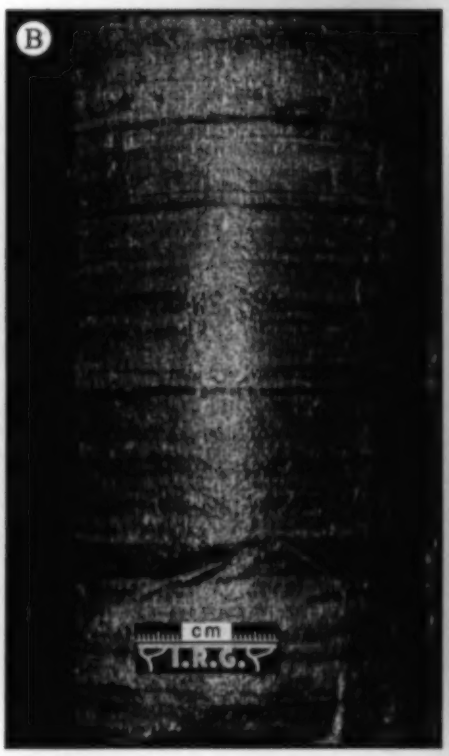


A. Gastropods and lithoclasts.
41/6-5-6-19W2/0, 2731.6m.

B. Peloids and broken up allochems.
21/8-17-13-13W2/0, 2147.9m.

C. Muddy sediments of Basal Lake Alma Member at Ceylon. This muddy nature causes them to be poor reservoirs.
41/10-18-5-20w2/0, 2569.0 m.

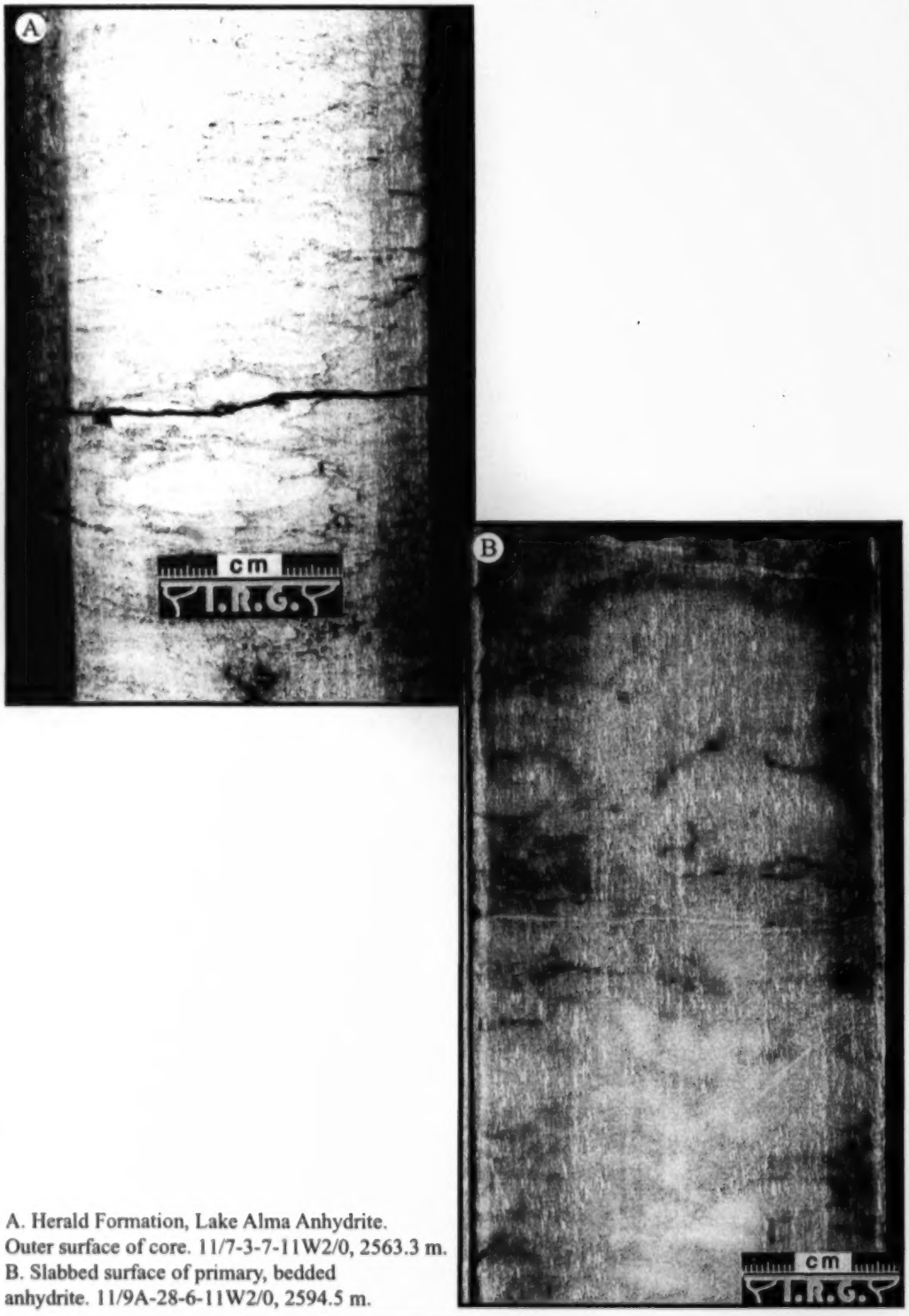
Figure 4.18 Facies 11: Laminated Dolomitic Mudstone



A. Bryozoans, peloids and algal mat fragments. Polarized light. Scale bar 500 μm. 41/7-17-13-13W2/0, 2154.4 m.

Lake Alma Dolomitic Member of the Herald Formation (Kendall, 1976)
B. 42/11-12-6-20W2/0, 2683.25 m.
C. 41/2-10-7-11W2/0, 2161.47 m.

Figure 4.19 Facies 12: Nodular Anhydrites



A. Herald Formation, Lake Alma Anhydrite. Outer surface of core. 11/7-3-7-11W2/0, 2563.3 m.
B. Slabbed surface of primary, bedded anhydrite. 11/9A-28-6-11W2/0, 2594.5 m.

CHAPTER 5. DIAGENESIS AND BURROW-RELATED DOLOMITIZATION IN THE YEOMAN FORMATION

5.1 INTRODUCTION

Diagenetic fabrics in the Yeoman Formation are closely related to biogenic sedimentary structures. This is especially true when examining the dolomitization patterns. Dolomite types are different within and adjacent to the burrow systems when compared to the dolomite found in the matrix. Strong controls on dolomite distribution are dispersed organic matter (DOM) and kerogen found in the sediment. The purpose of this chapter is to examine the various burrow types, and their associated diagenetic fabrics in order to determine if a certain type of biogenic sedimentary structure is responsible for the development of reservoir zones in the Yeoman Formation. Did certain burrow types create porous dolomite? As it will be shown, some secondary porosity development is related to burrows, but these do not produce adequate oil reservoirs. Producing zones are characterized by intercrystalline porosity, resulting from matrix dolomitization and dissolution. Furthermore, burrow related dolomite mottles are composed of non-porous, interlocking mosaics of non-planar dolomite, which generally have lower porosity than the matrix and thus reduce the overall reservoir potential of the rock.

5.2 BACKGROUND INFORMATION

Previous Studies

Most studies of the Yeoman Formation (Red River 'C' Burrowed Member) addressed the diagenetic processes, since they have such important economic implications. Dolomitization has created the best quality reservoirs. Due to the age and the deep burial of these Ordovician sediments, these rocks have a complex diagenetic history. Among the sequence of diagenetic events, dolomitization has been the most significant process imparting the present day appearance of these rocks and creating reservoirs throughout the Williston Basin. It is generally agreed that several dolomitization episodes have taken place (Kent and Haidl, 1999; Kendall, 1976, 1977; as well as others). Disagreements lie in the timing of dolomitization and the source of the dolomitizing fluids, particularly when addressing large-scale dolomitization events. Discrepancies in the models applied by various studies may be due to the disparity in the geographic location of the studies. Most studies indicate that the distribution of burrows and organic matter bear a close relationship to the distribution of dolomite.

Kendall's (1976, 1977) examination of the Bighorn Group comprised a thorough examination of diagenesis in the Yeoman Formation. He recognized at least two phases of dolomitization: early solution

cannibalization, which dolomitized the more permeable burrow fills, and later diagenetic dolomitization of the matrix. Kendall believed that the Yeoman epeiric sea could be compared to the modern Mediterranean sea, suggesting that many of the sediments were deposited as high-magnesian calcites, and recrystallization to more stable low-magnesian calcite provided Mg^{2+} for the dolomitization of burrow fills. Kendall observed that the matrix dolomitization increased downward; i.e. the subsurface Yeoman Formation is more dolomitized than the surface Tyndall Limestone. He did not believe a seepage-reflux type model, occurring during precipitation of the Lake Alma Anhydrite (facies 12), could be applied to the Yeoman Formation. Rather, he believed that the dolomitizing fluids were Devonian and penetrated the Yeoman sediments through faults and fractures.

Carroll (1978, 1979) also observed an increase downward in all diagenetic fabrics, including dolomitization. He also noted that burrow fills and haloes around them were preferentially dolomitized. Carroll believed that a mixing-zone (*sensu* Badiozamani, 1973) or Dorag model could explain the dolomitization pattern observed in the Red River 'D' porosity zone (equivalent of uppermost Yeoman) of North Dakota. This dolomitization model not only is under discussion and remains to be universally accepted (Machel and Mountjoy, 1986, 1987; Hardie, 1987); but would also require a fresh-water source in the Williston Basin. Yeoman deposition was subtidal, and a supply of fresh-water to dilute the waters of the entire Williston Basin "sea" to necessary salinities throughout the upper Ordovician is unlikely.

After examining cores in eastern Montana, Longman et al. (1983, 1987; Kendall et al., 1984) proposed a seepage-reflux type model for dolomitization of the Red River Formation. They found dolomite to be distributed in approximately circular pods, which consist of a central lens of cryptocrystalline dolomite, surrounded below and laterally by porous dolomite that interfingers with limestone. After subaerial precipitation of the overlying anhydrite (Lake Alma Anhydrite), magnesium-rich brines migrated down through fractures and other points of weakness in the anhydrite. Their evidence included the downward decrease in dolomitization, which is contrary to evidence presented by Kendall (1976, 1977) and Carroll (1978, 1979). Kendall et al. (1984) refuted this model, since the areal extent of dolomitization does not correspond to the areal extent of the anhydrite beds.

A model involving the refluxion of hypersaline brines during deposition of the Herald Formation (Laminated 'C' Member/Lake Alma Anhydrite) has also been adopted by many others (Clement, 1985; Ruzyla and Friedman, 1985; Kohm and Louden, 1988; Fox, 1993), with different factors controlling the distribution of the refluxing brines. Kohm and Louden (1988) believed that northeast-southwest lineaments controlled the Red River dolomitization in eastern Montana and western North Dakota. They found that in some areas, the sediments of the uppermost 'C' Burrowed Member are completely dolomitized, with the transitional lithology between the dolomite and unaltered limestone consisting of a rock type with dolomitized burrows in a limestone matrix. They inferred that the higher permeability of the burrows allowed the dolomitizing fluids to pass downward.

Zenger (1996a,b) compared the sedimentary and diagenetic fabrics in several upper Ordovician burrow-mottled platform carbonates of North America, which he named the Bighorn Dolomites (Zenger

and Lemone, 1995). The Steamboat Point Member of the Bighorn Dolomite (northwest Wyoming), 'C' Member of the Red River Formation (Montana) and the lower Upham Dolomite of the Montoya Group (west Texas) exhibited "impressive similarities". His findings, notably the downward decrease in dolomite, were consistent with those of Kohm and Louden (1978) and Longman et al. (1987). He proposed two episodes of dolomitization, the first being due to the downward refluxion of evaporitic water from the top of the 'C' zone. He believed that the burrows affected the dolomitization pattern by acting as conduits for the diagenetic fluids. Based on the geochemical signature of the dolomites and Na isotopes, the second episode, a deeper, burial neomorphism and stabilization, formed the coarser dolomite in the burrow-fills, the post-stylolitization dolomite and the dolomite overgrowths on the echinoderms. Magnesium for the second dolomitization episode would have been sourced from pressure solution of the earlier dolomite.

Kent and Haidl (1999) developed a model for dolomite formation in the Red River Formation in which fluids originated from localized basement structures and spread out along the kukersite rich layers. They did not believe that a seepage-reflux model could explain why some layers of rock are dolomitized and others are not. They postulated that dolomite formation could also have occurred during the periodic stagnation at the sea floor (*Gloeocapsomorpha prisca* algal blooms), with the dolomite precipitating at the sediment/water interface similar to the method described by Vasconcelos and Mackenzie (1997). Kent and Haidl (1999) noted that the aforementioned model would require that the kukersites and dolomite always follow a specific succession, with the dolomite overlying the kukersite, but this is not observed. It has been found in this study, that within a given oil pool although the kukersites are correlatable, the dolomite bodies are not (Figure 3.1).

While it has not been explicitly stated, there seems to be an inferred consensus that the dolomite associated with the burrows is early diagenetic, whereas the matrix dolomite formed at a later time. It has long been recognized that burrow fabrics control the onset of dolomitization in the Yeoman Formation, and this has also been found in other similar carbonate bodies. The activities of burrowing infauna can onset physical and chemical contrasts in the sediment, causing some sediments to be preferentially dolomitized. Since dolomitization is not a well-understood process, the physical and chemical conditions, which aid and which impede dolomitization are debatable. However, in sediments where the host rock has remained calcareous, but the burrows were dolomitized, the contrasts imparted by the burrows aided in the dolomitization. The following changes are produced by burrowing, and it remains to be established which conditions aid dolomitization.

Physical Modification of the Substrate

Bioturbating infauna alter the nature of the substrate by moving through it and re-arranging the sediment. Contrasting grain size, sorting and arrangement of grains cause the sediment to be more or less susceptible to dolomitization, and this has been recognized in both carbonate and clastic sedimentary rocks. Activities of infauna may impart the following physical modifications on the substrate, and many of these processes aid dolomitization.

1. Re-arrangement of particles: Burrowing infauna can either homogenize or sort the sediment, depending on the type of infaunal behaviour and the amount of bioturbation in the sediment (Bromley, 1996).
2. Changes in grainsize (Bromley, 1996). Particularly in carbonates, organisms may break down the skeletal fragments in order to ingest them. Due to the increased surface area of each grain, smaller grainsize is believed to make sediment more susceptible to dolomitization (Murray and Lucia, 1967). Preferential dolomitization of burrow fills, as well as surrounding sediment due to contrasting grain size has been observed in both ancient and recent sediments (Gunatilaka et al., 1987).
3. Altering the sediment compaction, and thus the water content of the substrate (Bromley, 1996).
4. Lining of burrows: Creating paths of preferential flow for diagenetic fluids, with the lined burrow containing the flow within the burrow.

The above listed activities of burrowing infauna increase or decrease the susceptibility of sediments to dolomitization by altering the surface area to rock volume ratio, as well as by altering the fluid flow potential of the substrate. Increased permeability of the burrow fills makes them preferential pathways for flow of diagenetic fluids. This leads those sediments to be more susceptible to dolomitization. The above models for dolomitization of mottled carbonates have been invoked as a control on dolomite distribution by several authors. Byers and Stasko (1978) believed that the presence of burrows controlled the localization of dolomitizing fluids by channeling them in the Ordovician McGregor Member of the Platteville Formation in Wisconsin. Many studies have documented similar observations (Griffin, 1942; Beales, 1953; Brown and Farrow, 1978; Gunatilaka et al., 1987).

Most burrowing organisms pump or circulate water through the burrow systems. This may in fact be an effective mechanism for introducing the necessary magnesium for dolomitization into the burrow environment. Seawater is believed to be an effective dolomitizing fluid, therefore potentially dolomitizing the sediments adjacent to the burrow while the organism still inhabits the burrow. Alternately, the magnesium may be held in place by mucous or an organic lining of the burrow. It thus remains there in quantities abundant enough to dolomitize the near-burrow sediments at a later time.

The burrow lining could potentially aid in dolomitization at a later time channeling the dolomitizing fluids through the burrow fill. This mechanisms could explain variability in the thickness of the diagenetic haloes found around burrows; i.e. the more effective the lining acts as a barrier to flow, the less dolomitizing fluid would leak out of the lining, thus resulting in a thinner diagenetic halo (compare Figures 2.4b, 4.9, 4.10, 4.13). Mucous and thin slimy films would not be preserved in the rock record, and this hypothesis can only be tested with experiments in modern studies.

Chemical Modification of the Substrate

The main points of debate surrounding the dolomite problem are the chemical conditions necessary for sediment dolomitization (Machel and Mountjoy, 1986, 1987; Hardie, 1987). Disagreement

surrounds what chemical factors, such as salinity, pH and oxidation, aid or inhibit dolomitization. Burrowing infauna alter the chemistry of the pore fluids in the burrow vicinity by various processes and thus creates microchemical environments where dolomite is preferentially precipitated. There are a number of ways in which the burrowers can alter the pore water chemistry:

1. Introduction of oxygenated sea-floor water below the redox boundary. Burrowing down below the redox boundary and introducing oxygenated fluids into the anoxic sediment. Mixing of the usual chemical zones in the substrate causes chemical reactions to take place.
2. Organic matter introduced into the sediment by organisms becomes host to bacteria and can lead to a host of chemical changes.
3. By secreting fluids or excrement, but also by ingesting grains and subjecting them to the intestinal acids.

The abundance of DOM/kerogen in the Yeoman Formation and its close relationship to the burrows suggests that the two are instrumental in the dolomitization patterns. The presence of organic matter within and lining burrows, which have been preferentially dolomitized, has been noted by most studies examining rocks with dolomitized burrows (Beales, 1953; Morrow, 1978; Gunatilaka, et al., 1987). Organogenic dolomitization has been the focus of several studies (Mazullo, 2000; Vasconcelos and Mackenzie, 1997; Slaughter and Hill, 1991; Baker and Kastner, 1981). Although some processes such as methanogenesis and sulfate reduction are known to aid dolomite precipitation, the exact chemistry will remain a mystery until the dolomite problem is solved.

Gingras et al. Burrow Related Organogenic Dolomitization Model

Since the mechanism of dolomitization remains a topic of discussion, it is impossible to accurately determine which conditions and processes lead to the dolomitization patterns in the Yeoman Formation and similar rocks. A burrow facilitated dolomitization model was proposed by Gingras (2000) after an examination of Tyndall Limestone, which is the lateral, outcrop equivalent to the Yeoman Formation. A series of steps as the sediment passes through the oxygenated substrate and is buried below the redox zone, facilitates dolomitization (Gingras, 2000). First, when the sediments are oxygenated, oxidation of the local organic matter produces CO_2. The increased CO_2 activity facilitates carbonate dissolution. Although he does not describe the distribution of the organic matter, it is suggested that since the dissolution occurs primarily in the burrows the organic matter is predominantly concentrated as burrow linings and in burrow fills. Sulfate ions (SO_4^{2-}) also present in the oxidizing substrates bonds with the free Mg^{2+}, thus lowering Mg/Ca ratio and inhibiting the dissolution and precipitation of dolomite. Gingras also believed that the abundance of NH_3 in the burrow microenvironment raises the pH of the interstitial fluids. A high pH facilitates the precipitation of dolomite by increasing the activity of the bicarbonate ion (HCO_3^-). This does not favour the replacement of calcite by dolomite. Gingras (2000) inferred that the dolomite replacement occurred once the substrate passed below the redox boundary. In the reducing environment, the sulfate ions would be consumed by sulfate reducing bacteria, thus freeing the Mg^{2+} ions. With this model, the early

calcite dissolution created permeability networks, which were then utilized by dolomitizing fluids in later stages of diagenesis.

5.3 Diagenetic Fabrics in the Yeoman Formation

Just as the facies in the Yeoman Formation have surprisingly uniform lateral consistency, the diagenetic fabrics associated with each of the facies are quite similar (Figure 4.1 – 4.4). Furthermore, although the original sedimentary facies are different, the diagenetic fabrics are surprisingly uniform across the facies. The different diagenetic descriptions seem to lie on a spectrum, which has the sediments least to most affected by dolomitization. Dolomitization is generally fabric destructive, often requiring the original nature of the rocks to be inferred from corresponding intervals in an adjacent or nearby well. This is difficult to do at the Ceylon Pool, because of the large distance between the wells in comparison to the Tyvan and Midale Pools.

5.3.1 Diagenetic Fabrics at the Midale Pool

The Midale Pool has been one of the most extensively studied Red River/Yeoman oil pools in southern Saskatchewan (Canter, 1998; Kent and Haidl, 1999; as well as others). This pool is valuable in this study because of the close placement of cored wells available for examination. There is also a great contrast in the extent of dolomitization between some of the wells, allowing the sedimentary structures and diagenetic structures to be compared: notably, the comparison of the two wells Berkley et al. Midale 11/7-3-7-11W2/0 and 41/2-10-7-11W2/0. The latter is not as affected by dolomitization as the former. The contrasts in the extent of dolomitization between different Midale wells suggests that although primary sedimentary structures controlled the distribution of diagenetic fabrics, large scale controls affected the extent to which each well is dolomitized.

Midale Facies 1.

This facies is penetrated only in the two deepest wells (11/7-3-7-11W2/0 and 41/2-10-7-11W2/0), thus due to well control, comparison of diagenetic fabrics is limited. Although this zone is locally mottled, the mottles do not exhibit the burrow-like pattern characteristic of other Yeoman Facies (Figure 4.8). The mottles are due to greater dolomite content. The matrix is calcareous, with unimodal, porphyrotopic, planar-e dolomite crystals ranging generally between 20 and 40 μm (Figure 5.1a,b). These dolomite crystals comprise between 40 and 50% of the rock. The mottles are made of approximately 85% dolomite, which is subhedral (planar-s) and unimodal, ranging between 40 and 60 μm (Figure 5.2a,b). Porosity is low in both the matrix and mottles, mostly < 3%. Allochems are commonly replaced by drusy calcite, but some are partially dolomitized. Pressure solution is indicated by suturing between allochems. Locally, a late calcite cement is present, occluding the matrix porosity.

Midale Facies 2.

Facies 2 is observed in two separate diagenetic facies. The matrix remained undolomitized at the Berkley et al. Midale 41/2-10-7-11W2/0 well (Figure 5.3a). At most of the other Midale wells however, the matrix is extensively dolomitized (Figure 5.3b). Locally, the matrix remained partially dolomitized. Diagenetic fabrics in Facies 2 are very similar to those in Facies 1, except the dolomite mottles are more distinct and are clearly closely related to burrows. Whereas in Facies 1 burrows are not always visible in the mottles, in Facies 2 on slabbed sections burrows can be identified. In all the Midale cores, the mottles consist of a unimodal, interlocking mosaic of non-planar dolomite crystals, which average 40 μm (Figure 5.4a). The walls of these mottles are gradational and crystals grade from non-planar to sub-planar and to planar crystals in the matrix. The abundance of allochems in the mottles also decreases towards the center of the mottle. The mottles may contain lined or unlined burrows within them. These type of mottles occur throughout the Yeoman Formation in most facies and all the pools. They will be hereto be described as Type 1 mottles (Figure 2.7). Variations will be noted as they occur within each facies. Unmagnified, the unlined burrows are distinguished by color contrast with the rest of the sediment. Under magnification, these burrows are commonly more difficult to see. In many cases, they contain less DOM/kerogen, and thus their fill has a lighter color. The dolomite crystals in the burrow core may be slightly larger than the mottle crystals, also causing the burrow fill to appear lighter in color.

At Berkley et al. Midale 41/2-10-7-11W2/0, there are more scattered allochems within the mottles. The burrow cores here have also been commonly replaced by slightly coarse dolomite (averaging 60 μm), locally by saddle dolomite with the crystals ranging up to 1 mm. The micrite contains scattered planar-e dolomite crystals, ranging from 10 to 40 μm. Here dolomite comprises ~15% of the matrix. In the more dolomitized wells, the matrix sediment is usually unimodal, planar-e and planar-s dolomite crystals between 20 and 80 μm, averaging 40 μm (Figure 5.4b). Matrix dolomitization is fabric destructive, since where the matrix sediment remained calcareous (41/2-10-7-11W2/0), it contains more abundant and diverse allochems with better preservation. Intercrystalline porosity found in the matrix is variable, but it ranges around 10%.

Facies 2 also occurs recurringly between the kukersites in the upper portion of the Yeoman. The matrix also remained undolomitized in these carbonate-kukersite cycles at the 41/2-10-7-11W2/0 well. The matrix is calcareous micrite with scattered, planar-e dolomite rhombs, averaging 20 μm. The sediment contains mottles consisting of 20-60 μm subhedral dolomite, which has a 5% calcite cement component. At this well, there is also another type of mottle, which consists of planar-s 40-60 μm porphyrotopic dolomite crystals. The carbonates of facies 2 provide the lowermost producing zone in the Yeoman Formation at Midale. Generally, the more extensive the dolomitization, the more extensive the porosity development (Figure 4.1, 4.2). The matrix contains 20% intercrystalline porosity, whereas the mottles only have approximately 5% porosity consisting of fracture and moldic burrow porosity. In the more dolomitized intervals, the matrix consists of polymodal, planar-s and planar-e crystals, ranging between 50 and 60 μm. The mottles consist of unimodal, mostly non-planar mosaic of dolomite crystals, averaging 60 μm. These

type 1 dolomite mottles appear to be diagenetic haloes and not *Thalassinoides* as believed by some since the dolomitization front is truncated by allochems. Sutured allochem contacts indicate pressure solution. Saddle dolomite is found throughout Midale in fractures and in the burrow cores in the mottles.

Midale Facies 3.

The matrix of Facies 3 has resisted dolomitization in the Midale pool. It is comprised of cryptocrystalline calcite (<< 5 μm), that has approximately 50% porphyrotopic, planar-e dolomite crystals ranging between 20 and 40 μm (Figure 5.5a,b). The dolomite mottles (Type 1) are made up of an unimodal, interlocking mosaic of planar-s and non-planar crystals ranging between 40 and 60 μm. This is low porosity zone, which is easily distinguishable on well logs (Figure 4.1, 4.2), has less than 5% porosity, which is limited to fractures and solution seams.

Midale Facies 4.

Many of the kukersites exhibit extensive pressure solution at the Midale Pool. This, combined with the abundant bitumen and DOM/kerogen, makes these sediments poor for thin section analysis. The two most commonly observed diagenetic fabrics are pressure solution and dolomitization. Although not all kukersites are dolomitized (Figure 3.1), the thin sectioned ones are. The porphyrotopic, planar-e dolomite crystals, averaging 60 μm, are contained within a cryptocrystalline calcite and organic matter and commonly bitumen as well (Figure 5.6a,b). There is a range in crystal size, with an increase in dolomite corresponding to an increase in the disseminated B *G. prisca* macerals. The fractures are infilled with saddle dolomite crystals, which have increasing crystal size towards the center of fractures. Porosity is limited to fracture porosity.

Midale Facies 5.

In most of the Midale pool, Facies 5 sediments are completely dolomitized, except for at the least dolomitized well, Berkley et al. Midale 41/2-10-7-11W2/0 (Figure 5.7a). There the matrix is cryptocrystalline calcite containing 10-20 μm scattered planer-e dolomite rhombs, which comprise 5% of the sediment. At the aforementioned well, mottles are also cryptocrystalline calcite, with porphyrotopic planar-e dolomite crystals that comprise approximately 60% by visual estimation (< 10-40 μm crystals). The mottle walls are sharp. The precursor sediments are likely to have been mudstones because both the matrix and the mottles are mudstone. In the more dolomitized wells, the matrix consists of bimodal dolomite crystals. The smaller crystals are 5 μm planar-s and planar-e crystals. Approximately 15% of the crystals average 80 μm planar-e. The mottles consist of planar-s and non-planar dolomite, averaging 50 μm. These mottles also have quite sharp walls (Figure 5.7b). At the 41/2-10-7-11W2/0 well, neither the mottles, nor the matrix have any porosity. In the more dolomitized wells, the matrix may contain up to 15% intercrystalline porosity. Molds after halite hopper crystals commonly occur in the dolomite mottles. These

have been occluded by cements: first by saddle dolomite, followed by anhydrite and finally calcite (Figure 5.7c).

Midale Facies 6.

The diagenetic fabrics of facies 6 greatly resemble those in Facies 2 and 3. The matrix remained undolomitized throughout the Midale pool and it consists of cryptocrystalline calcite with unimodal, porphyrotopic, planar-e dolomite crystals comprising about 10% of the sediment (20-40 μm in size, Figure 5.8a). The dolomite mottles have formed more commonly around burrows lined with organic matter, leaving the unlined burrows in the matrix undolomitized. The mottle dolomite is Type 1 like elsewhere, a unimodal, interlocking mosaic of non-planar dolomite crystals, averaging 40 μm. The crystals within the burrow cores are commonly coarser than in the mottle (Figure 5.8b). The mottle wall consists of a gradational contact grading from the non-planar crystals in the mottles, through planar-s crystals, to scattered planar-e crystals in the matrix. Generally, the matrix and mottles have little porosity, other than fractures. Locally, burrow cores have been dissolved out, contributing a vuggy porosity. Elsewhere, they are partially or completely cemented with saddle dolomite and anhydrite. Again, the anhydrite postdates the saddle dolomite. Allochems are generally recrystallized into drusy calcite.

Midale Facies 7.

This zone is extensively dolomitized, and here the original textures and earlier diagenetic fabrics are difficult to distinguish due to extensive washout textures. The matrix comprises mostly planar-s and planar-e dolomite rhombs ranging from 20-80 μm (Figure 5.9a). In some zones, these crystals have a bimodal distribution, with large and small planar-e dolomite crystals, the former averaging 40 μm and the latter averaging 5 μm. The mottles consist of unimodal, non-planar, interlocking mosaic of dolomite crystals, 40 μm (Figure 5.9b). At 41/2-10-7-11W2/0, the matrix is not completely dolomitized, but consists of approximately 50% planar-e dolomite rhombs (Figure 5.10a). The pore spaces commonly contain saddle dolomite, which is polymodal, ranging 10 to 50 μm. Many allochems are preserved within single crystal dolomite syntaxial overgrowths. Porosity is mainly in the matrix, and it is generally greater than 15%, locally ranging up to 30%. However, that may be an overestimation of the subsurface conditions because of the crumbly nature of the core. The porosity is almost exclusively intercrystalline. Fracturing has increased it locally (Figure 5.10b). The porosity size is much less than the dolomite crystal size in the matrix. The dolomite mottles have less than 5% porosity, generally limited to fracture porosity.

Midale Facies 8.

Mudstones of Facies 8 are dolomitized. The most conspicuous diagenetic fabrics of this zone are some large diagenetic nodules, which although conspicuous to the naked eye (Figure 5.11a), lose their contrast with the adjacent sediment under microscopic magnification (Figure 5.11b). At the Midale pool, these nodules are fabric preserving. When examined under thin section, the nodule appears to have less

bitumen staining and DOM, suggesting that this nodule is a result of recrystallization, which has minimally decreased the porosity. This unfortunately does not show up well on microphotographs.

Midale Facies 9.

The dolomitization patterns in Facies 9 are the same as those found in facies 2 and 6, with the exception that matrix dolomitization, where present, has not created intercrystalline porosity. More commonly this interval remained resistant to dolomitization (Figure 5.12a). Porosity is limited to minor intercrystalline porosity, commonly found within burrows (Figure 5.12b). Two notable diagenetic fabrics give this interval a distinctive appearance. First, the presence of abundant silica nodules, which are found exclusively in this interval. Second, the stylo-mottled nature of this interval is present in all the examined wells.

5.3.2 Diagenetic Fabrics at the Tyvan Pool

The Tyvan Pool sediments are shallower than the Midale and Ceylon Pools sediments. Diagenetically this has imparted the greatest difference in that the organic matter has a lower maturity, not having reached the oil window. Thus diagenetic fabrics are better preserved because bitumen staining has not occluded the porosity as extensively.

Tyvan Facies 2.

This facies is penetrated only in the deepest well in this pool, Tri Link Tyvan 21/8-17-13-13W2/0. The diagenetic fabrics are surprisingly similar to those observed in this facies at Midale. The matrix consists of cryptocrystalline calcite, with approximately 15% of it being porphyrotopic, polymodal planar-e dolomite rhombs, ranging from 20-100 μm (Figure 5.13a). The mottles are same as Type 1 mottles described at Midale. They consist of unimodal, non-planar dolomite, averaging 0.04 mm. Minor, less than 5%, anhydrite cement is also found in these samples. The porosity here, like at Midale, is contained in the matrix. Generally, the sediments contain 5% intercrystalline porosity, locally reaching 15%. Locally some intrafossil porosity is observed. The mottles on the other hand, have no porosity except for fractures, which are only found in the mottles. Approximately 50% of the allochems are dolomitized, some only partially. Some allochems are calcareous with a dolomite envelope. Syntaxial overgrowths occurred on many of the echinoderm debris. Some brachiopods are replaced by dolomite with fabric preserving replacement.

Tyvan Facies 3.

Although facies 3 at Tyvan is generally richer in allochems, here too it has resisted complete dolomitization. The matrix consists of calcareous dolomite with 20-50% calcite (Figure 5.13b). Much of the calcite component consists of undolomitized allochems, but minor cryptocrystalline calcite is observed in the matrix. The dolomite consists of unimodal, scattered dolomite rhombs, which are planar-e and planar-s. The greater the calcite content, the higher proportion of planar-e relative to planar-s dolomite

rhombs. The rhombs average 40 μm in size. The mottles are type 1, as described in the Midale Pool diagenetic fabrics. The unimodal, non-planar mosaic crystals average between 40 and 60 μm, but the mottles also contain some larger planar-s dolomite rhombs, which are 80 μm. The mottles also contain between 5 and 10% calcite. There are << 5% allochems in the mottles, suggesting that these mottles are indeed fabric destructive diagenetic haloes, which have formed around the burrows.

The porosity is mainly in the matrix, with the porosity being intercrystalline (estimated ~ 5-10%) and having sizes generally much smaller than the crystal sizes. With the exception of some fracture and moldic burrow porosity, there is almost none in the mottles. Here the burrow cores have been hollowed by dissolution, forming hollow burrow cores, which may extend along the burrow axis for several millimeters. Locally, these pore spaces are occluded by saddle dolomite cement, which appears to be the last diagenetic event in this facies.

Tyvan Facies 4.

The kukersites at Tyvan exhibit very similar diagenetic fabrics to those at Midale, except for the fact that the DOM/kerogen here are not mature with respect to hydrocarbon expulsion. This leaves them having a reddish-brown color rather than the black color observed at Ceylon and Midale. These kukersites are also generally dolomitized, with the dolomite consisting of unimodal, planar-e dolomite rhombs averaging 40 μm in size (Figure 5.14a,b). Dolomite crystals in the fill of *Planolites* are slightly coarser than in the matrix.

Tyvan Facies 6.

This zone is not extensively sampled, with only one thin section cut from a zone typified as Facies 6. The matrix consists of cryptocrystalline calcite, with planar-e porphyrotopic dolomite crystals, ranging between 5 and 20 μm. The mottles are Type 1, non-planar dolomite, with crystals averaging 30 μm. The porosity is visually estimated to be 10-15%. Fracturing and dissolution have greatly enhanced porosity and permeability in this zone (Figure 5.15a). The fractures are commonly solution enlarged. Many of the burrow cores are also hollow, with some locally enlarged by dissolution. Bitumen staining occurs in both the matrix and the mottles (Figure 5.15b). This zone differs from Facies 6 at Midale and Ceylon by the extensive dissolution porosity, solution enlarged fractures and hollowed out burrow cores, which have created valuable reservoirs.

Tyvan Facies 7.

In many wells, this facies is so extensively stained by bitumen that thin section analysis is futile. This zone is extensively dolomitized, with the latest dolomitization episode creating sucrosic dolomite. The sucrosic dolomite is greatest in lenses, as in Midale, which suggests that grainstone lenses are often thus dolomitized due to their greater permeability. A sample cut from a core piece, which is cleaned of its bitumen was also examined from this zone. The matrix and mottles are both dolomite. The matrix is

composed of polymodal, dolomite ranging between 20 and 100 μm (Figure 5.16a), with some being saddle dolomite. The mottles are a unimodal, mosaic of non-planar dolomite crystals averaging 50 μm. The mottles also contain some saddle dolomite crystals of 10 μm. Consistent with other zones, the porosity is concentrated in the matrix. Visually, the porosity is estimated to be between 15 and 20%; however, this may be increased due to the crumbly nature of the core. The mottles have lower porosity ranging between 5 and 10%. Some allochems have micritic rims, other syntaxial overgrowths. Anhydrite cements are also common in this interval (Figure 5.16b). Locally, burrow fills have higher porosity than the matrix, but due to the size of these burrows and the extensive dolomitization, classification of these burrows is not possible (Figure 5.17a).

Tyvan Facies 8.

Facies 8 at Tyvan is not completely dolomitized. These sediments consist of cryptocrystalline calcite with approximately 30% being porphyrotopic, planar-e dolomite rhombs ranging between 20 and 40 μm. This zone does not contains dolomite mottles, but rather the fill of some *Planolites* were even less susceptible to dolomitization than the matrix (Figure 5.17b). Only 10% of their fill consist of the scattered dolomite rhombs. The peculiar diagenetic nodules found at the Midale pool are also observed here (Figure 4.15). They exhibit a greater variety in types. Some are early and some are late. The syndepositional timing of formation of some of these mottles has been inferred from the displacive nature of some of these nodules. Elsewhere, burrows and sedimentary laminae can be traced into the nodule (Figure 4.15). Some of the nodules are calcareous, others dolomitic. Chertified nodules are also observed.

Tyvan Facies 9.

Diagenetic fabrics in facies 9 are similar to those found in undolomitized facies 6 and 9 at Midale. The matrix in this zone generally remained undolomitized, with sediment dolomitization restricted to the burrows and haloes around them. The calcareous matrix is cryptocrystalline, but lacks the scattered dolomite rhombs. The lined burrows commonly have type 1 mottles, but the unlined ones remained calcareous. Pressure solution is unique in that it formed along the mottle walls, giving some intervals of this facies a characteristic stylo-mottled appearance (Figure 5.18a,b). As at Midale, the formation of siliceous nodules is common. Locally, in peloidal storm beds, 5-10% interparticle porosity is observed, otherwise this zone has quite low porosity.

5.3.3 Diagenetic Fabrics at the Ceylon Pool

The sedimentary facies at the Ceylon Pool do not correlate as clearly with the Midale and Tyvan Pool Facies; however, the diagenetic fabrics are not very different from those at Tyvan and Midale. Exploration in this pool was not successful as at Tyvan and Midale. Cores were examined with the hope of finding a clue related to ichnology and diagenesis, which may explain the poor oil production observed at this pool.

Ceylon Facies 1.

Facies 1 at Ceylon is much like at Midale, except that the matrix has undergone extensive dolomitization. The cryptocrystalline calcareous matrix contains 90% dolomite, which has a bimodal distribution (Figure 5.19a). The smaller dolomite crystals consist of porphyrotopic, planar-e crystals ranging from 20-80 μm. The larger dolomite crystals are syntaxial overgrowths on allochems, mostly echinoderm debris, averaging between 0.5 and 1 mm. The dolomite mottles are Type 1. They consist of planar-s and non-planar, interlocking crystals, generally finer than in other zones (less than 20 μm). Some of the planar-s crystals at the mottle walls may be up to 40 μm in diameter. Generally, facies 1 has no porosity in either the matrix or the mottles, but where the matrix is dolomitized this facies may have up to 10% fracture and intercrystalline porosity (Figure 5.19b).

Ceylon Facies 2.

The matrix in Facies 2 consists of dolomitic limestone, and the diagenetic fabrics are consistent with those in this facies at Midale and Tyvan. The cryptocrystalline calcite contains scattered dolomite rhombs averaging 40 μm in size (Figure 5.20a). *Planolites* fills may be dolomitized, but commonly these lack the dolomitic halo. There are few, thin dolomite haloes around dolomitized *Palaeophycus* (Figure 5.20b). These mottles are also Type 1 mottles (unimodal, non-planar, interlocking mosaic of 10-20 μm dolomite crystals). The mottle dolomite is here also fabric destructive. Some calcareous allochems are enclosed within dolomitic haloes. Some allochems are preserved within syntaxial overgrowths of dolomite, which may be greater than 1 mm. The cores of many *Palaeophycus* are dissolved, and now are cemented by saddle dolomite (Figure 5.21a). Halite hopper molds are observed in many of the dolomite mottles, and many of these molds are now been cemented by saddle dolomite (Figure 5.21b). Porosity in this interval is limited to fractures and intercrystalline matrix porosity, which may be as much as 15%.

Ceylon Facies 4.

Diagenetic fabrics in the kukersites at Ceylon closely resemble those at Midale. Most of them are completely dolomitized (Figure 5.22a). Where they are not, the sediment consists of bitumen, DOM/kerogen and cryptocrystalline calcite, which contains at least 50%, scattered dolomite rhombs, which are 5 μm (Figure 5.22b). Many of these kukersites have been intensively burrowed, and the planar-s dolomite crystals at the core of *Asterosoma* and *Rhizocorallium* are slightly coarser (10-20 μm). Other common diagenetic fabrics are from the precipitation of pyrite and pressure solution (Figure 5.22c).

Ceylon Facies 6.

Diagenetic fabrics of facies 6 at Ceylon are very similar to those at the undolomitized intervals of facies 6 at Midale. As elsewhere, a cryptocrystalline calcite contains scattered dolomite rhombs and type 1 dolomite mottles (Figure 2.7c, 5.23a). The scattered dolomite rhombs are bimodal, either 20-40 μm planar-e rhombs or 0.1-0.2 mm syntaxial overgrowths on allochems. This facies has the best porosity development

(< 10%) at Ceylon, which consists of intercrystalline and fracture porosity. Burrow cores and many fractures have been cemented up by saddle dolomite (Figure 5.23b).

Ceylon Facies 8.

Planolites mudstones are generally extensively dolomitized at the Ceylon pool (Figure 5.24). The dolomitization did not destroy the recognizability of the burrows. This facies is mottled by two textures of dolomite, one being more porous than the other. Generally, what appears to represent burrows consists of the higher porosity, planar-e 20 μm dolomite crystals. The matrix, on the other hand, is an interlocking mosaic of less-porous, planar-s dolomite crystals (40-60 μm). The more porous burrow fills may have as much as 30% porosity (generally 10%), whereas the matrix reaches only 10% porosity (generally < 5%). Where *Palaeophycus* are observed in facies 8, their core is cemented by saddle dolomite.

5.4 The Role of Bioturbation in Dolomitization

The different facies of the Yeoman Formation examined in the 3 oil pools exhibit surprisingly uniform diagenetic fabrics. It is the objective of this study to determine if a relationship exists between the burrow types and diagenetic fabrics. Although one can generalize that the lined burrows more commonly have dolomitized burrow fills and haloes, than do the unlined ones, this can not be made a rule. A more accurate generalization would be that although *Planolites* are found in the mottles, they are more commonly found undolomitized in the matrix. Furthermore, burrows lined with calcareous allochems and lacking macerals and kerogen also commonly remained undolomitized. No absolute relationship can be deduced about burrow types and whether they are dolomitized or not. In fact the uniform pattern of dolomitization associated with significantly different trace fossils is surprising. This suggests that there are a few other factors at play, and inferences can be made about the timing of dolomitization.

It appears that the nature of the lining played a crucial role in determining whether the burrow is dolomitized. Unfortunately, the samples examined for the nature of the lining (Chapter 3), did not contain any of the lined ichnospecies without dolomite haloes. Nor did they contain any *Planolites* without dolomite mottles. A more detailed examination of the assemblages of organic matter in the dolomitized and undolomitized, lined and unlined burrows of the Yeoman Formation would prove to be fruitful in understanding the controls on dolomitization. It seems plausible that the type of maceral influenced the precipitation of dolomite, since the amount of matrix dolomite seems proportional to the abundance of organics in the matrix. Stasiuk (pers. comm. 2002) noted that the abundance of dolomite is greater with increased abundance of *G. prisca* alginite in the sediment. He agrees that there seems to be a relationship between the two. This is also consistent with the observations of Kent and Haidl (1999).

The uniform dolomitization pattern associated with the burrows throughout the entire Yeoman Formation and age equivalent, similar formations has been noted by others (Zenger and Lemone, 1995). The observed uniformity suggests that the controls on dolomite mottle formation were early diagenetic. If the dolomitizing fluids seeped through post-lithification either during Lake Alma Anhydrite precipitation

(Longman et al., 1987) or during the Devonian (Kendall, 1976, 1977), the preferentially dolomitized burrows would not be so uniform throughout such a large area. First, as mentioned by Kendall et al. (1984), the areal extent of the Lake Alma Anhydrite is not comparable to the areal extent of the Yeoman Formation. Second, the dolomitizing fluids would have had to spread uniformly through interconnected burrow systems, throughout the entire formation to produce such a uniform dolomitization pattern. The causative burrows and their dolomite haloes, are not in uniform abundance and are not always interconnected. Furthermore, one would expect then that other high permeability zones and zones adjacent to them should exhibit the same dolomitization. Comparable grainstone lenses, however, commonly remained undolomitized. Finally, the non-planar fabric of the dolomite, suggesting that abundant magnesium was available (Sibley and Gregg, 1987), is consistent throughout. The availability of Mg^{2+} for dolomite precipitation had one of two likely sources. Magnesium may have been held in the burrow linings by organic matter and mucus as described by Over (1995). Another alternative is that the magnesium source was seawater, which circulated through the burrow systems either while the organism lived, or after. A combination of these mechanisms could also have served as a magnesium source.

There is no observed decrease in the burrow related dolomite pattern downwards from the top of the formation. The downward decrease in dolomite can only be said about the matrix dolomite, suggesting that the fluids responsible for matrix dolomitization flowed downwards. The burrow-related dolomitizing fluids must therefore have been an earlier fluid. Another piece of evidence for this is the differential mechanical compaction of the dolomite mottles and the host sediment. This suggests that the mottles formed in those intervals prior to complete lithification of the host sediment. The above combined evidence indicate that the burrow-related dolomitization was a syndepositional to early diagenetic event. Early dolomitization of burrows also has been commonly observed in recent sediments (Gunatilaka et al., 1987), and dolomitization of burrows in the Yeoman Formation probably occurred under similar processes as described in their study.

5.5 Diagenetic History of the Yeoman Formation

All the Yeoman facies, other than the *Planolites* mudstone, appear to have undergone a similar diagenetic pathway, however, in different intervals, matrix dolomitization was halted at different stages. Many of the early diagenetic fabrics were destroyed by later diagenesis, particularly in the more extensively dolomitized zones. No evidence for early cements are observed. They appear to have been obliterated by subsequent diagenesis. Some early dissolution took place at the sea floor, as shown by the rare geopetal structures in allochem molds.

Mottle dolomitization, of both burrow fills and diagenetic haloes, appears to have been an early diagenetic event. Other than the previously discussed evidence, this is supported by the presence of pseudomorphs after halite crystals (Figure 2.6a, 4.12a, 5.25a), which occur exclusively in the non-planar dolomite mottles. In order for these halite crystals to have grown, either the surrounding sediment must have been unlithified, or they would have to have grown in a void space. There is little evidence to suggest

that in all the zones where these halite pseudomorphs are found, the mottles were open burrows (Figure 2.6a). Locally, there are burrow collapse structures, but these are relatively rare compared to the abundance of pseudomorphs after halite. This would suggest that when the halite crystals grew, the adjacent sediment was displaced.

In certain intervals (Figure 5.25b), fractures are observed in the dolomite mottles, which are filled by matrix sediment. Presumably lithification accompanied the formation of the dolomite mottles. Lithification followed in some zones, but more likely lithification and early dolomitization occurred concomitantly. The mottles rarely show evidence of mechanical compaction. However in some zones, particularly in the nodular zones, the surrounding sediment exhibits evidence of differential compaction relative to the dolomite mottles (Figure 3.8a). Evidence of mechanical compaction is generally in the larger allochems, the smaller ones rarely show evidence of this.

Dissolution is also observed. Hollowed out burrow cores and solution enlarged fractures are common, but moldic, fabric selective dissolution porosity after allochems is rare. Where not occluded by later diagenetic cements, the hollowed out 'moldic burrow porosity' can enhance reservoir quality. Where applicable, matrix dolomitization occurred next, and it may have been an ongoing process. In some places the matrix remained entirely calcareous, and the percentage of matrix dolomite ranges from 0 to 100%. The matrix dolomite is planar-e, generally porphyrotopic contained in a micritic calcareous matrix. Dolomite may be present as syntaxial overgrowths on echinoderm fragments. The abundance of this dolomite is not proportional to the abundance of allochems present in the matrix, and, where the matrix is extensively dolomitized, the precursor fabrics are commonly difficult to discern. The echinoderm fragments are best preserved in the dolomite. Mechanisms of matrix dolomitization are probably a result of a larger scale dolomitization process and this has been extensively examined (Longman et al., 1987; Kendall, 1976; as well as others). A regional examination of wells, necessary to examine large-scale dolomitization models, is beyond the scope of this study. The distribution of matrix dolomite was controlled by larger scale features, such as faults, fractures and the extent of overlying anhydrite beds. When comparing the closely spaced wells in the Midale pool, it becomes apparent that the dolomitized zones can not be correlated (Figure 3.1). This is important in hydrocarbon exploration, since the intercrystalline porosity present in the matrix provides much of the valuable reservoir.

Pressure solution and fracturing followed the matrix dolomitization. Commonly fractures extend from the stylolites. Stylolites are common in the Yeoman Formation and range from micro-stylolites to thick concentrations of organic matter, which suggests an entire kukersite bed may have been removed by pressure solution. Pressure solution was an ongoing process that may have occurred several times during the diagenetic history of the Yeoman Formation. Dissolution followed the fracturing event at Tyvan (Figure 5.25c), and to a lesser event at Midale; but, this was rare at Ceylon. This is a probable cause of lower exploration success at Ceylon.

Saddle dolomite precipitation is common in all facies of the Yeoman Formation and the mechanisms of its precipitation are currently being examined by Qing (2001). This saddle dolomite is

found as a void-filling cement in hollowed out burrow cores and fractures, and also filling the molds of the halite hopper crystals. The presence of fractures in both the matrix and mottles suggests that the saddle dolomite post-dates a fracturing event. These fractures are common and are not occluded by late cements in the Tyvan pool, and it is thus the fracture and dissolution porosity, which creates valuable reservoirs in the examined Tyvan wells. Reservoir potential in part is poor at Ceylon due to the relatively greater abundance of the saddle dolomite. These wells are buried deeper and it is plausible that saddle dolomite would be more abundant in deeper wells.

Anhydrite is not an abundant cement, and it is found in greatest abundance at the Midale pool. From crosscutting relationships, the anhydrite cement is found to postdate the saddle dolomite (Figure 5.7c). The sulfate rich fluids penetrated only some intervals, generally with the anhydrite being more common in the reservoir zones of the Midale pool. Anhydrite is found in only very minimal amounts at Tyvan and Ceylon pools. Since this mineral is localized and concentrated in particular intervals, the source likely penetrated these intervals through fractures and faults.

Late calcite cement precipitation appears to be the latest diagenetic event in many of the Midale pool wells. Evidence is from poikilotopic textures, where anhydrite and saddle dolomite crystals are enclosed in the calcite cement.

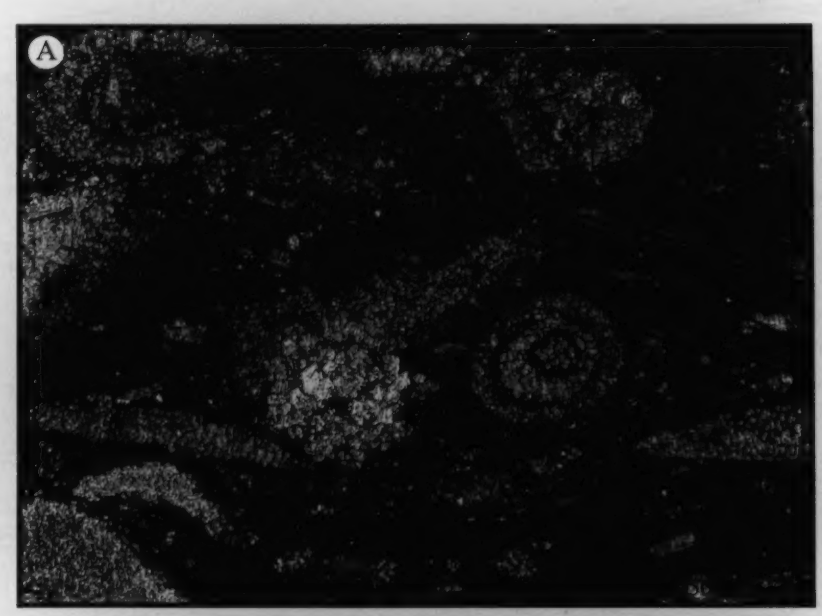
Facies 8, *Planolites* mudstone, exhibits various degrees of dolomitization, with this facies being most extensively dolomitized at Ceylon (Figure 5.24c). At Tyvan dolomitization is incomplete. At Ceylon, dolomitization has caused the burrow fills to have a higher intercrystalline porosity than the matrix, which is the opposite of what is observed in all the other facies. These, however, are not enough to produce significant hydrocarbon reservoirs.

Producing intervals in the Yeoman Formation are characterized by intercrystalline porosity development (Figure 4.1 – 4.4). This was also observed elsewhere (Fox, 1993). Locally, fractures and dissolved burrow cores enhance the reservoir quality of the rocks. Since matrix dolomitization was a large-scale process, regional studies are more valuable in determining the dolomitization mechanism responsible for reservoir development. The Ceylon oil pool was not a successful exploration target because it did not have the extensive matrix porosity development that is observed at Tyvan and Midale. Since the succession of sedimentary facies at Ceylon are slightly different from the Midale and Tyvan, and considering the distance between this pool and the other two, the observed differences in diagenetic fabrics is to be expected. Overall, the Ceylon sediments are not as rich in allochems, with fabrics generally being muddier. This initial nature of the sediments made them more susceptible to the formation of non-planar dolomites. The non-planar interlocking mosaics rarely contain the intercrystalline porosity, which produced the valuable reservoirs in the other two oil pools. There are fewer kukersite beds in the Ceylon oil pool, and many have been extensively reworked (Figure 4.11). A lower availability of source rocks may have caused the Ceylon oil pool not to be economically valuable.

5.6 Conclusions and Recommendations

In the facies of the Yeoman Formation, except the *Planolites* Mudstone Facies 8, similar diagenetic fabrics are observed. They vary along a spectrum of least to most dolomitized fabrics. On one end of the spectrum the burrow fills are dolomitized and are contained within a calcareous matrix. At the other end of the spectrum, both the matrix and burrows are completely dolomitized. The diagenetic fabrics that affect each sedimentary facies are generally consistent, varying from least to most dolomitized. The extent of matrix dolomitization generally increases upward to the top of the Yeoman Formation, correlating with the increase in organic matter in the sediment. However, this is a generalization, which is not always observed, and the uppermost Yeoman Facies locally remain unaffected by dolomitization. The pattern of burrow-related dolomitization, however, is quite consistent throughout. The various ichnospecies do not have varying diagenetic fabrics. Evidence from diagenetic patterns and the uniformity of burrow-related dolomite suggests that this dolomite is early diagenetic. Further examination of the assemblages of organic matter in burrow linings may be fruitful in determining if a certain maceral variety caused the sediment to be more prone to dolomitization than others.

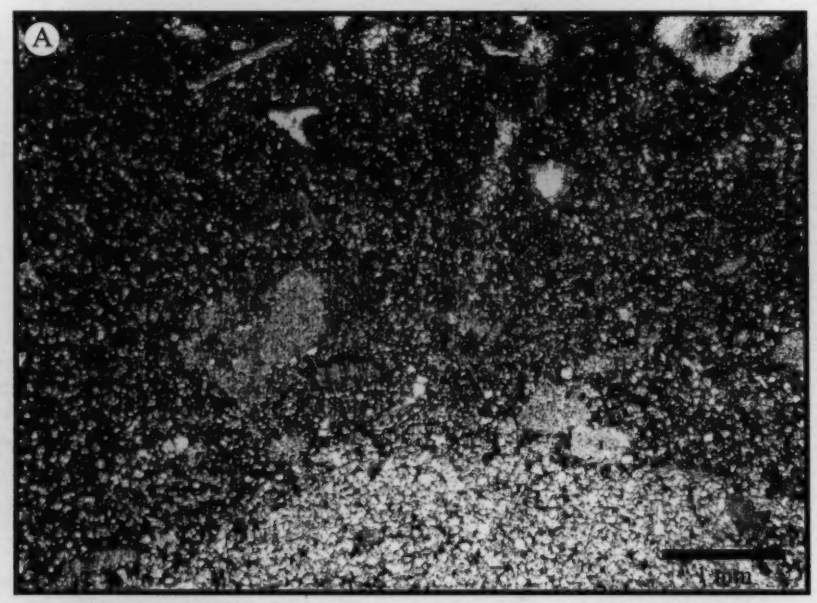
Figure 5.1 Midale Pool Diagenesis: Facies 1



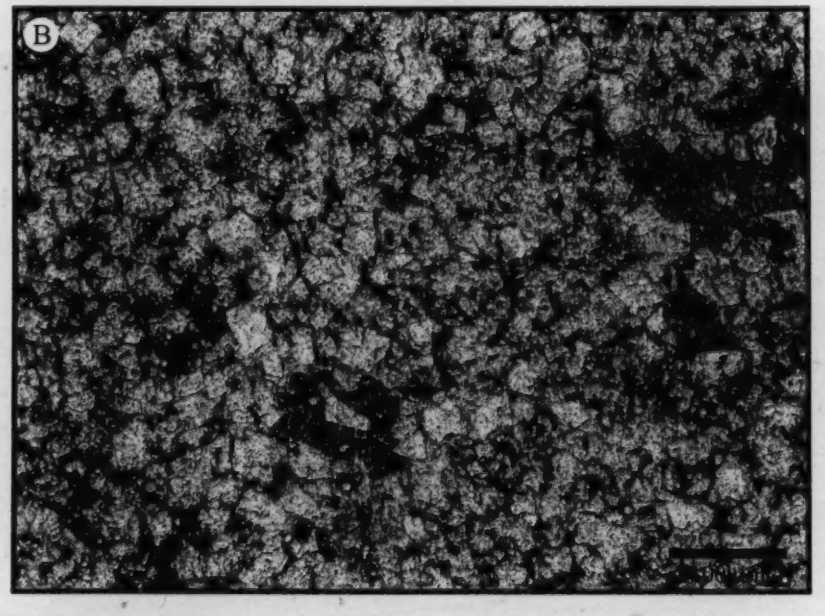
A. Calcareous matrix with scattered planar-e dolomite rhombs. Polarized light. Scale bar 500 μm. 11/7-3-7-11W2/0, 2611.8 m.

B. Dolomite mottle wall and matrix dolomite. Polarized light. Scale bar 100 μm. 11/7-3-7-11W2/0, 2611.8 m.

Figure 5.2 Midale Pool Diagenesis: Facies 1

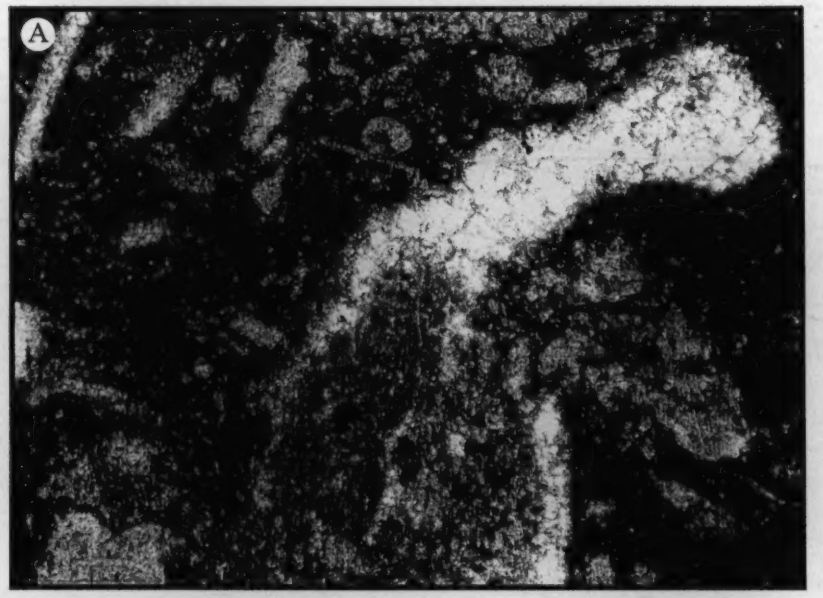


A. Dolomite mottle wall. Polarized light. Scale bar 1 mm. 11/7-3-7-11W2/0, 2611.8 m.

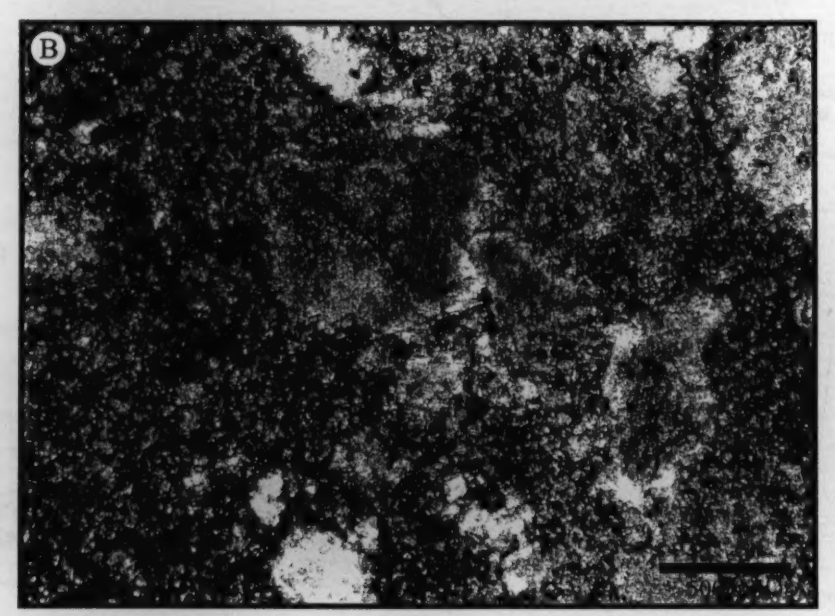


B. Planar-e and planar-s mottle dolomite. Polarized light. Scale bar 100 µm. 11/7-3-7-11W2/0, 2611.8 m.

Figure 5.3 Midale Pool Diagenesis: Facies 2

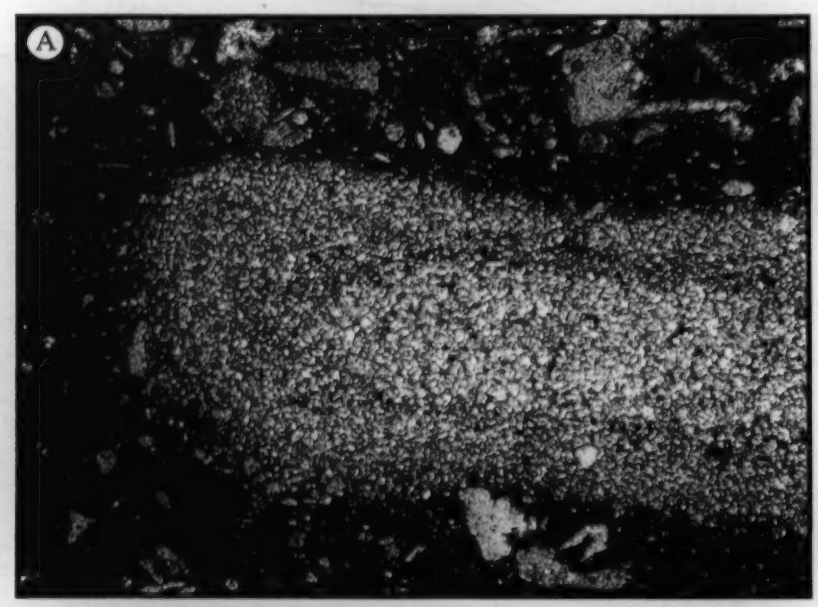


A. Calcareous matrix with allochems in an undolomitized well. Polarized light. Scale bar 500 μm. 41/2-10-7-11W2/0, 2594.0 m.

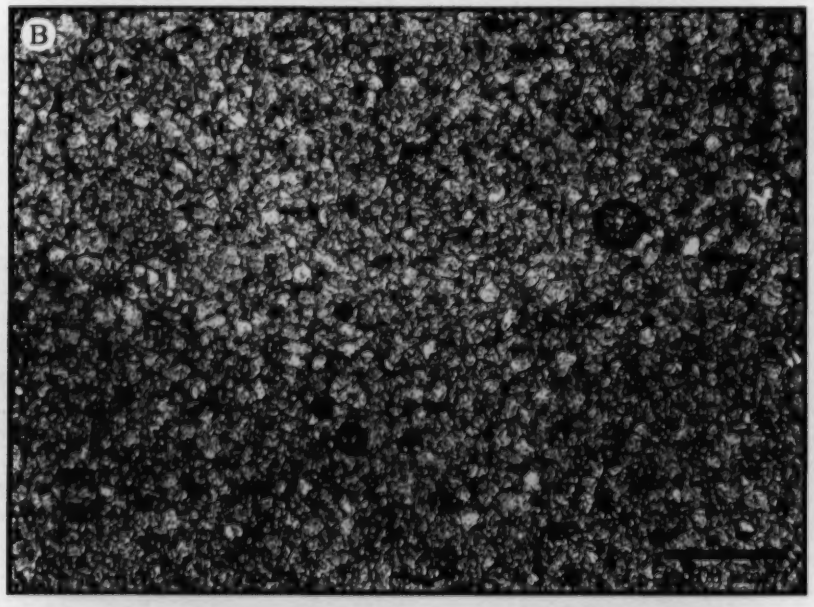


B. Intercrystalline matrix porosity in a dolomitized well. Polarized light. Scale bar 500 μm. 11/7-3-7-11W2/0, 2600.5 m.

Figure 5.4 Midale Pool Diagenesis: Facies 2



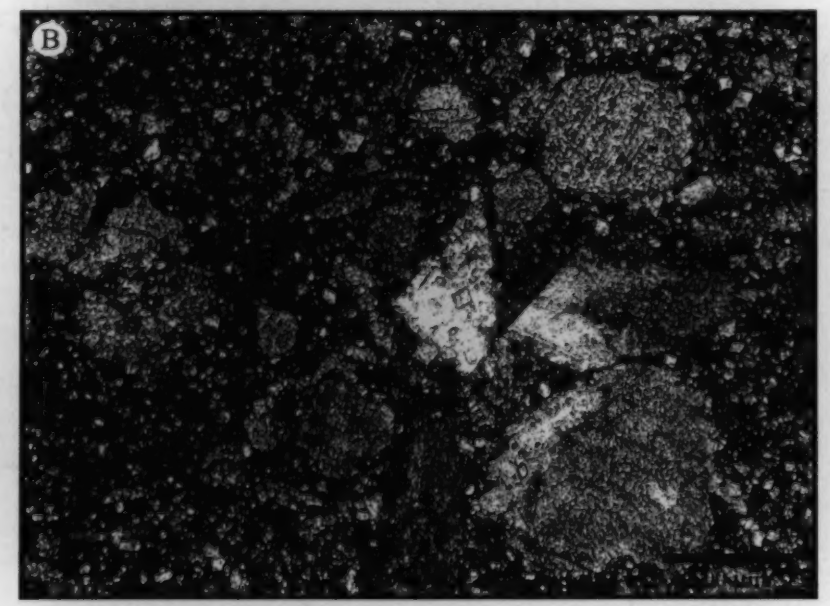
A. *Palaeophycus* with type 1 dolomite mottle. Polarized light. Scale bar 1 mm. 41/2-10-7-11W2/0, 2592.9 m.



B. *Palaeophycus* with type 1 dolomite mottle from a dolomitized interval. Intercrystalline porosity in matrix blue at bottom of image. Polarized light. Scale bar 100 μm. 11/7-3-7-11W2/0, 2604.5 m.

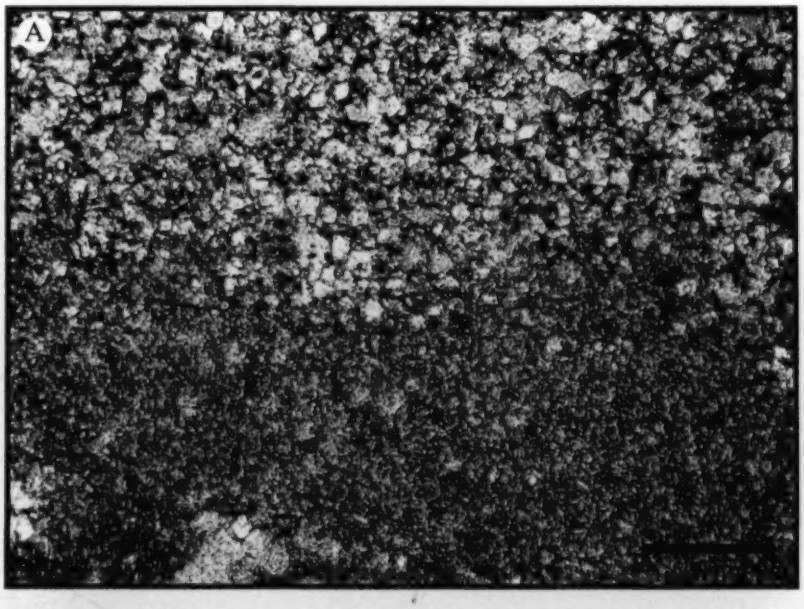
Figure 5.5 Midale Pool Diagenesis: Facies 3

A. Calcareous mudstone and wackstones with scattered planar-e dolomite rhombs. Note pressure solution. Polarized light. Scale bar 500 µm. 21/11-35-6-11W2/0, 2600.2 m.

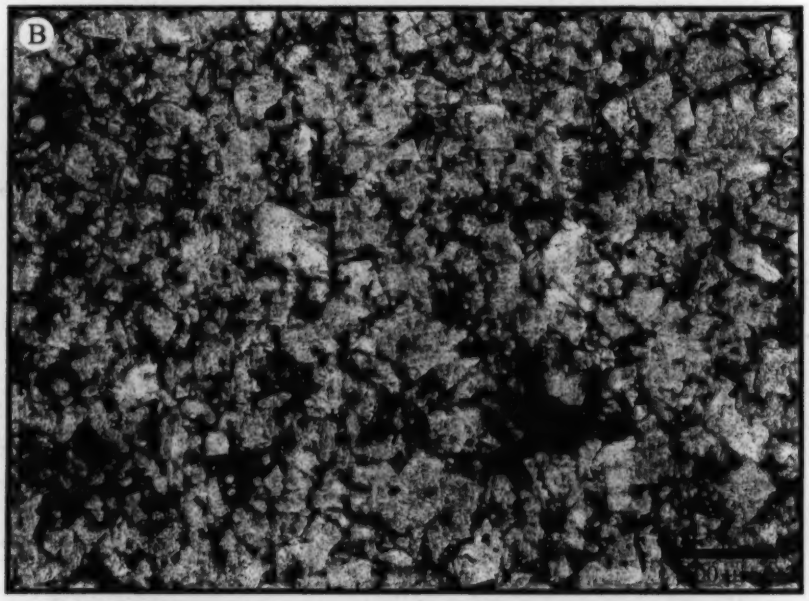


B. Syntaxial dolomite overgrowths. Polarized light. Scale bar 500 µm. 01/12-2-7-11W2/0, 2590.3 m.

Figure 5.6 Midale Pool Diagenesis: Facies 4

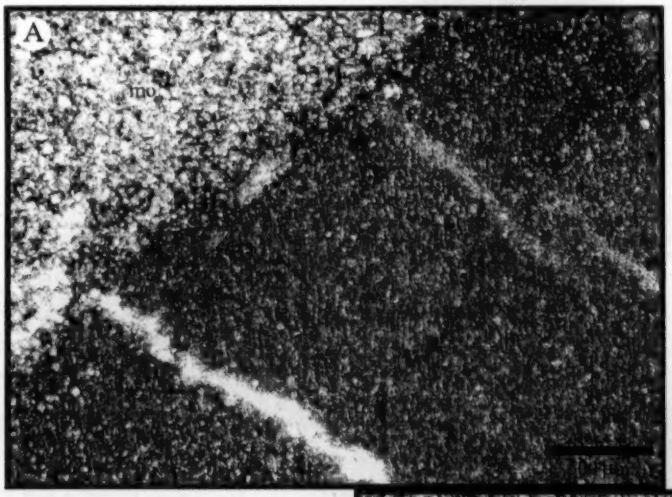


A. Firmground base of kukersite in Figure 3.5a. Kukersite was more extensively dolomitized than the calcareous sediment below. Polarized light. Scale bar 500 μm. 41/2-10-7-11W2/0, 2181.2 m.

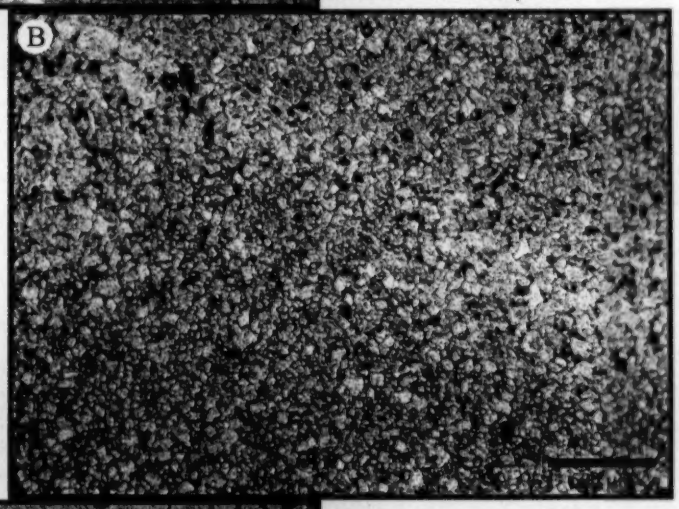


B. Dolomitized fill of *Thalassinoides* underlying kukersite in Figure 3.5a. Polarized light. Scale bar 100 μm. 41/2-10-7-11W2/0, 2181.2 m.

Figure 5.7 Midale Pool Diagenesis: Facies 5



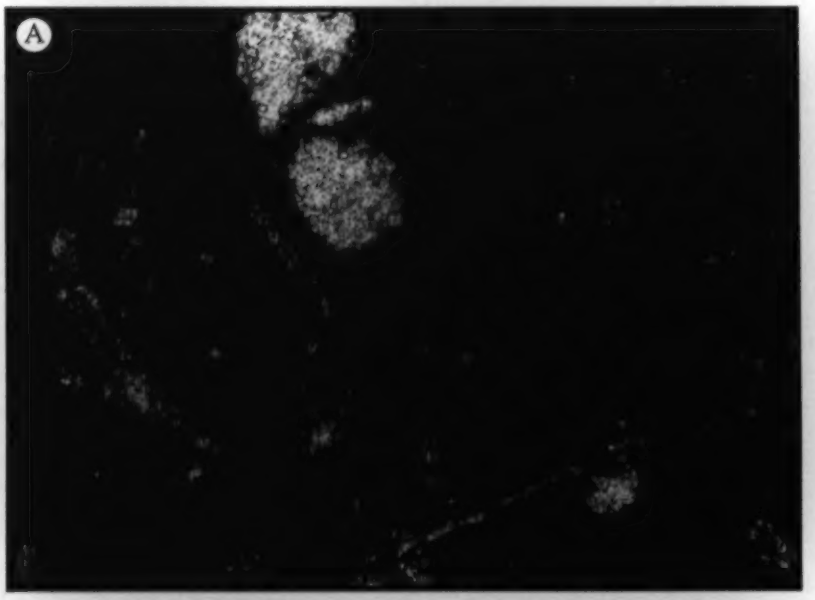
A. Matrix and mottle with fracture in an undolomitized well. Polarized light. Scale bar 500 μm. 41/2-10-7-11W2/0, 2586.6 m.



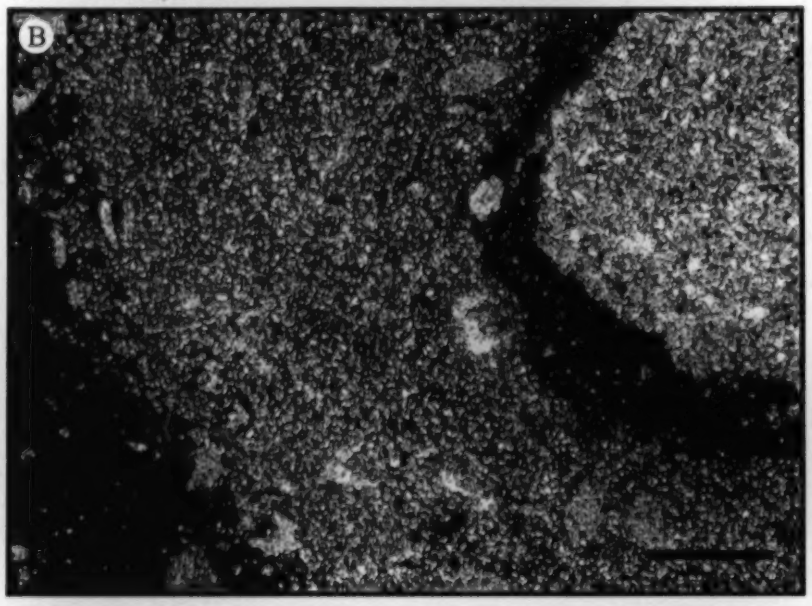
B. Matrix (ma) and mottle (mo) in a completely dolomitized interval. Polarized light. Scale bar 500 μm. 21/11-35-6-11W2/A, 2591.5 m.

C. Molds of halite hopper crystals, cemented by saddle dolomite (D), anhydrite (A) and calcite (C). Non-polarized light. Scale bar 500 μm. 31/11-34-6-11W2/A, 2606.1 m.

Figure 5.8 Midale Pool Diagenesis: Facies 6

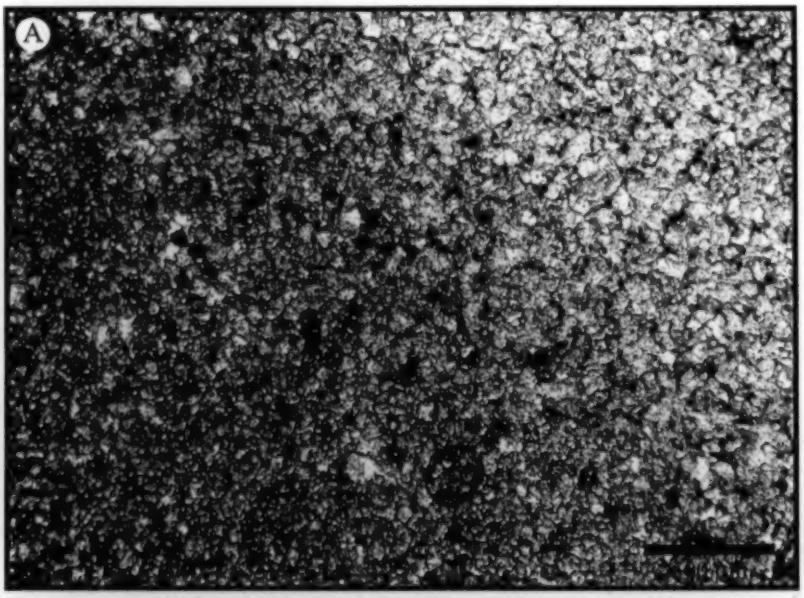


A. Calcareous matrix with allochems, in an undolomitized well. Echinoderm fragment (E). Fracture porosity (F). Polarized light. Scale bar 100 μm. 11/7-3-7-11W2, 2582.4 m.

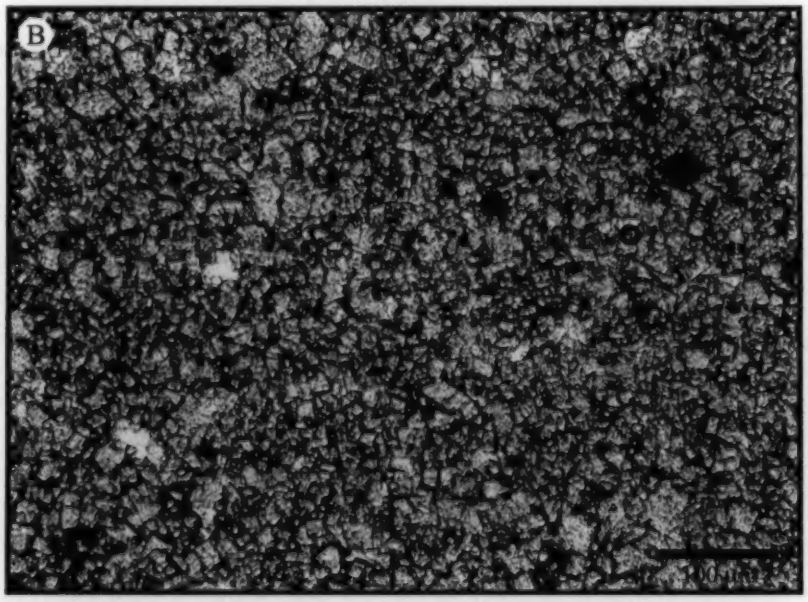


B. *Palaeophycus* lined with *G. prisca*, with Type 1 dolomite haloe. Burrow core (B). Dolomite haloe (H). Polarized light. Scale bar 1 mm. 11/7-3-7-11W2/0, 2582.4 m.

Figure 5.9 Midale Pool Diagenesis: Facies 7

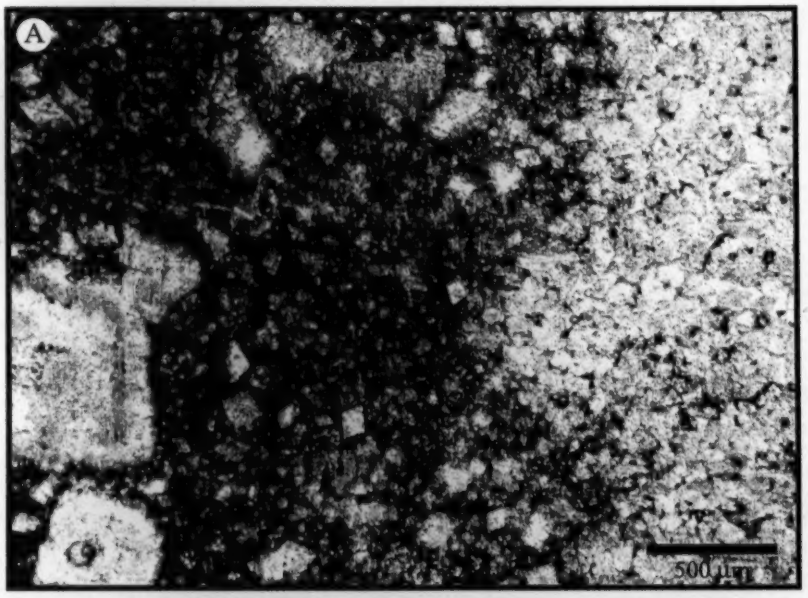


A. Dolomite mottle and matrix with intercrystalline porosity. Polarized light. Scale bar 500 μm. 11/7-3-7-11W2/0, 2581.1 m.

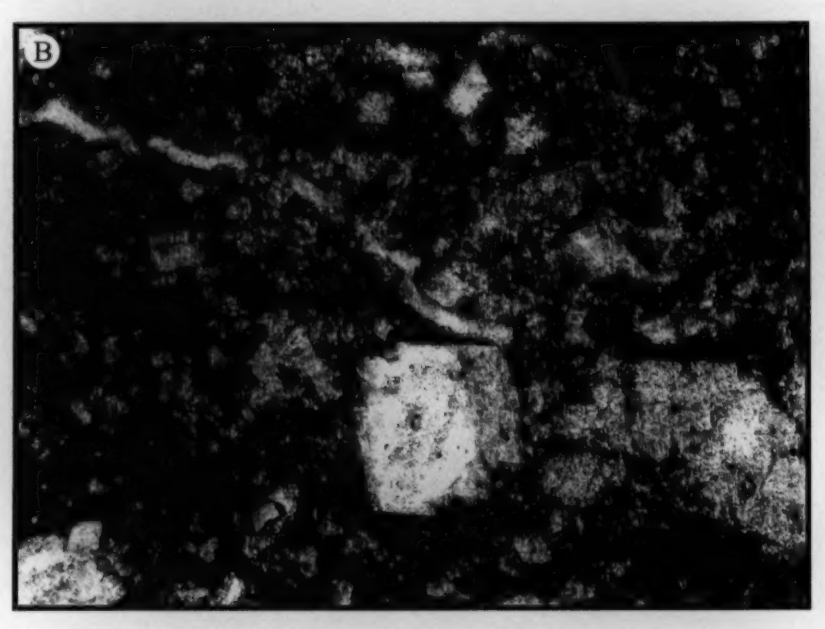


B. Matrix dolomite: planar-e dolomite rhombs with intercrystalline porosity. Polarized light. Scale bar 100 μm. 11/7-3-7-11W2/0, 2581.1 m.

Figure 5.10 Midale Pool Diagenesis: Facies 7



A. Calcareous matrix with allochems, in an undolomitized well. Polarized light. Scale bar 500 µm. 41/2-10-7-11W2/0, 2578.8 m.



B. Intercrystalline and fracture porosity, in a partially dolomitized matrix. Polarized light. Scale bar 100 µm. 41/2-10-7-11W2/0, 2578.8 m.

Figure 5.11 Midale Pool Diagenesis: Facies 8

A. Diagenetic nodule. *Planolites* in B: TS. Dashed line indicates nodule wall. 31/11-34-6-11W2/A, 2596.2 m.
B. *Planolites* crossing through the nodule wall. Burrow fill has less organics and bitumen than the surrounding matrix. Porosity occluded by late calcite cement. Dashed line indicates nodule wall. 31/11-34-6-11W2/A, 2596.2 m.

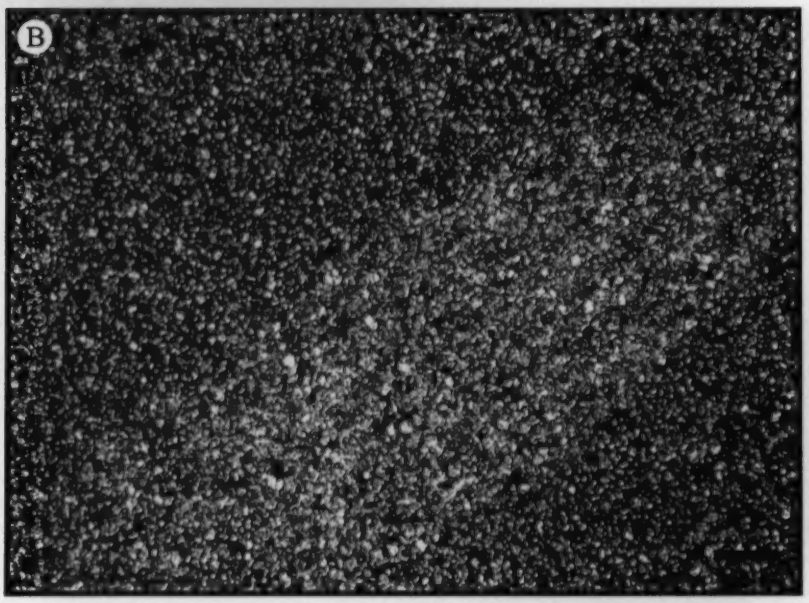
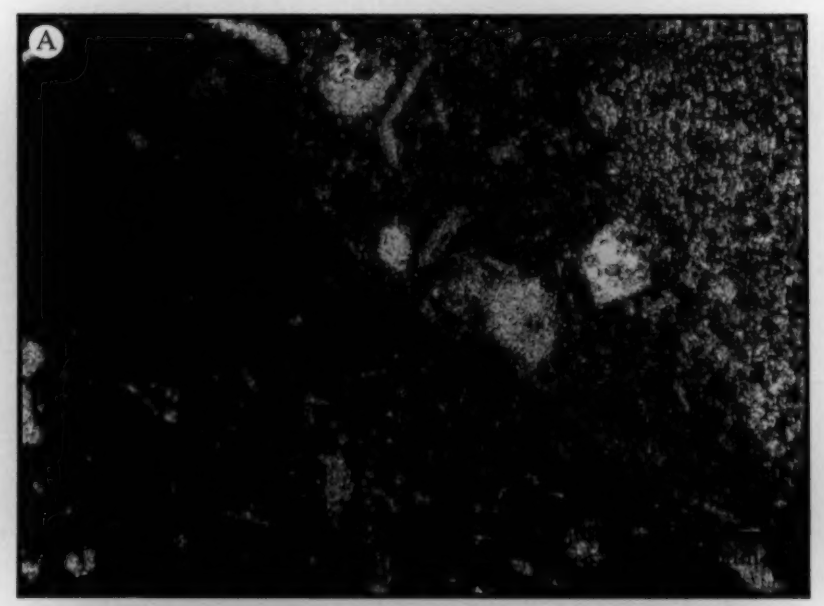
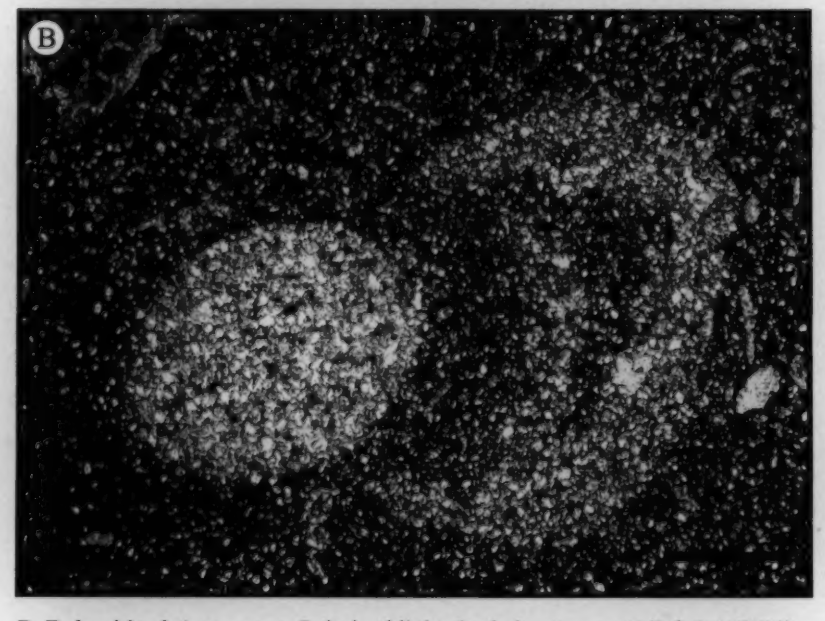


Figure 5.12 Midale Pool Diagenesis: Facies 9

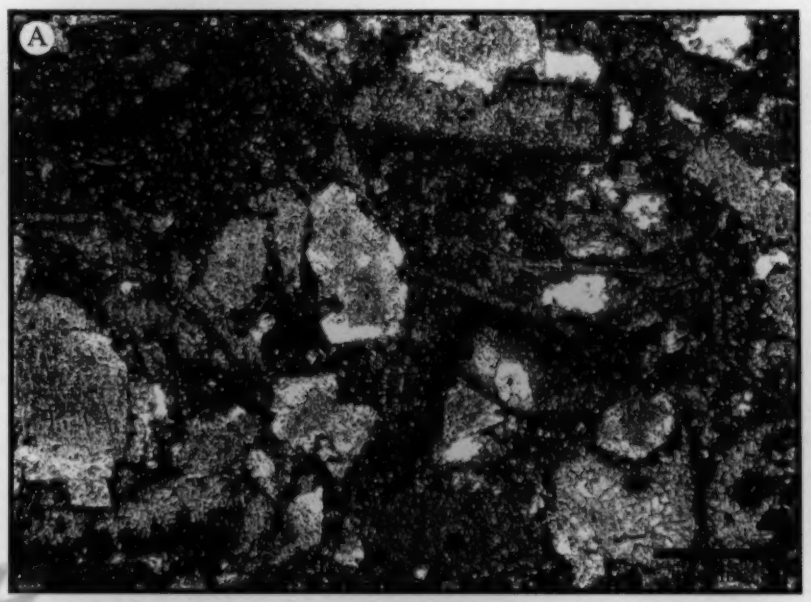


A. Calcareous matrix and *Palaeophycus* in an undolomitized well. Polarized light. Scale bar 500 μm. 41/2-10-7-11W2/0, 2574.3 m.

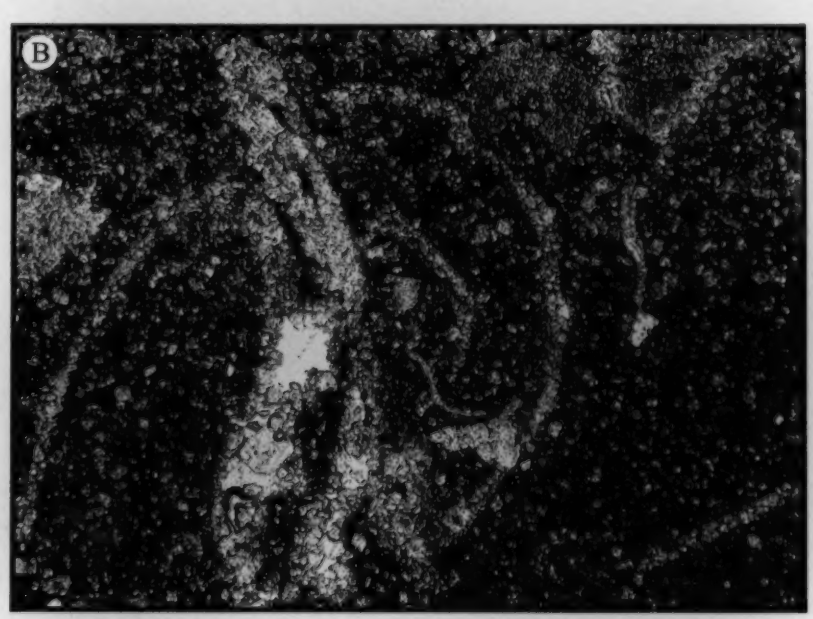


B. Dolomitized *Asterosoma*. Polarized light. Scale bar 1 mm. 11/7-3-7-11W2/0, 2577.0 m.

Figure 5.13 Tyvan Pool Diagenesis: Facies 2 and 3

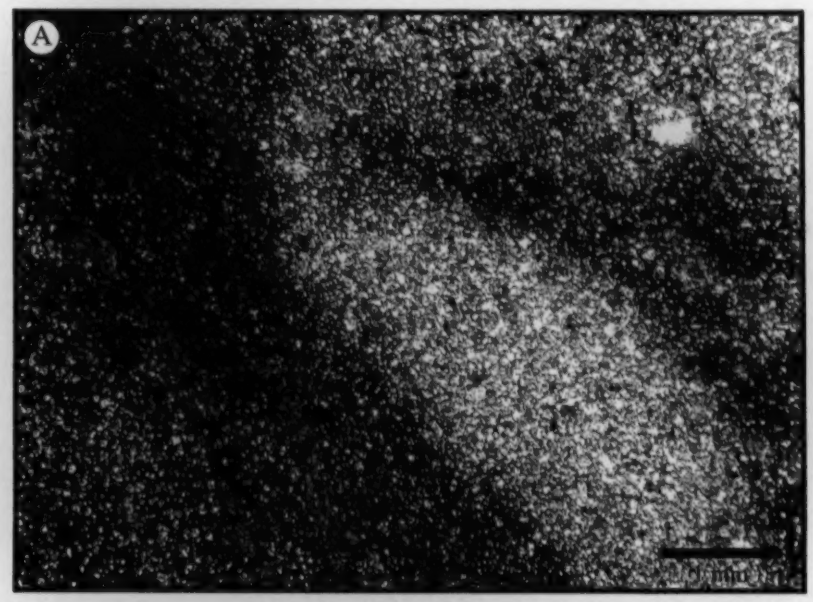


A. Facies 2, allochems and porosity in a partially dolomitized matrix. Polarized light. Scale bar 1 mm. 21/8-17-13-13W2/0, 2170.9 m.

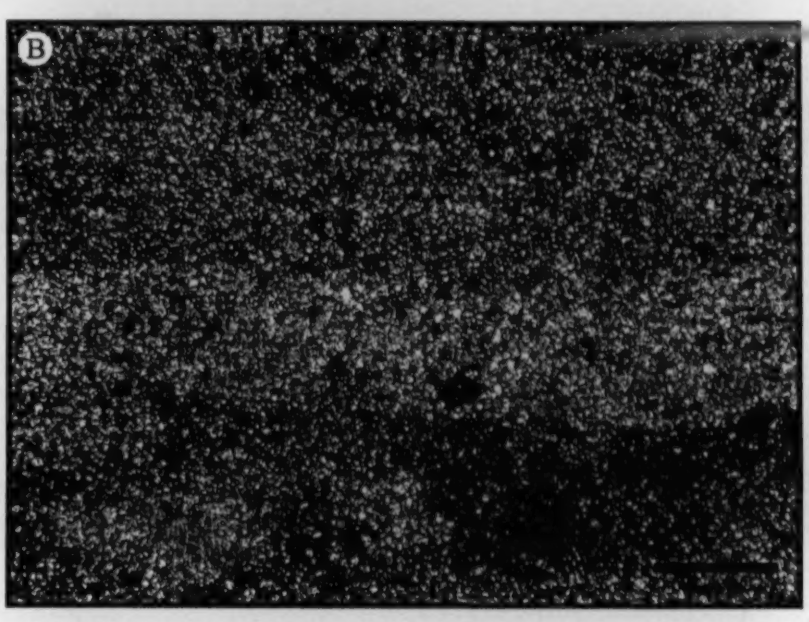


B. Facies 3, allochems and moldic porosity. Polarized light. Scale bar 500 µm. 21/8-17-13-13W2/0, 2167.3 m.

Figure 5.14 Tyvan Pool Diagenesis: Facies 4

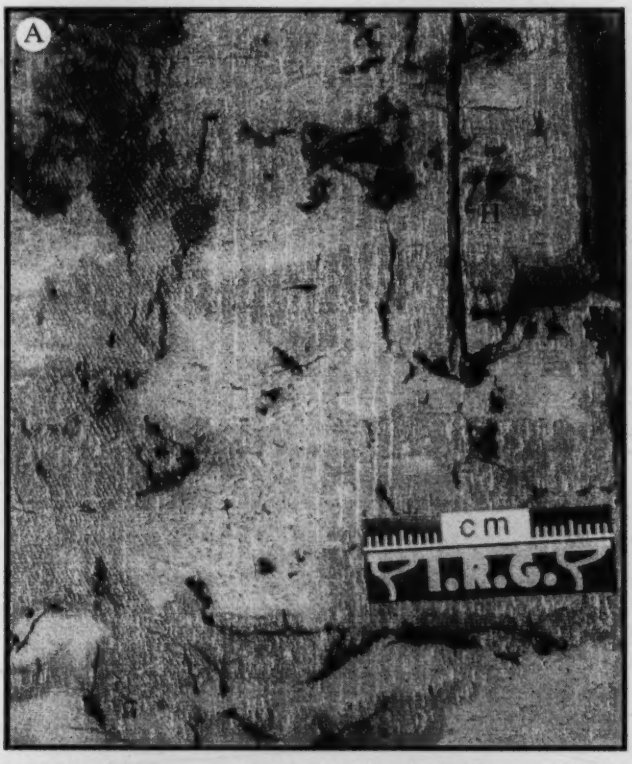


A. Organic laminae and *Planolites* in a dolomitized kukersite. Polarized light. Scale bar 1 mm. 41/7-17-13-13W2/0, 2167.6 m.

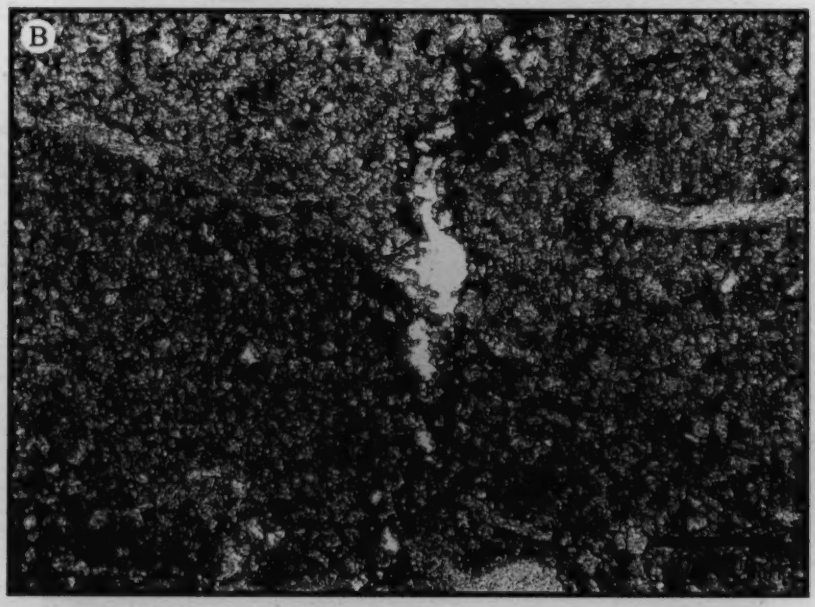


B. *Planolites* in a kukersite. Polarized light. Scale bar 1 mm. 41/7-17-13-13W2/0, 2167.6 m.

Figure 5.15 Tyvan Pool Diagenesis: Facies 6

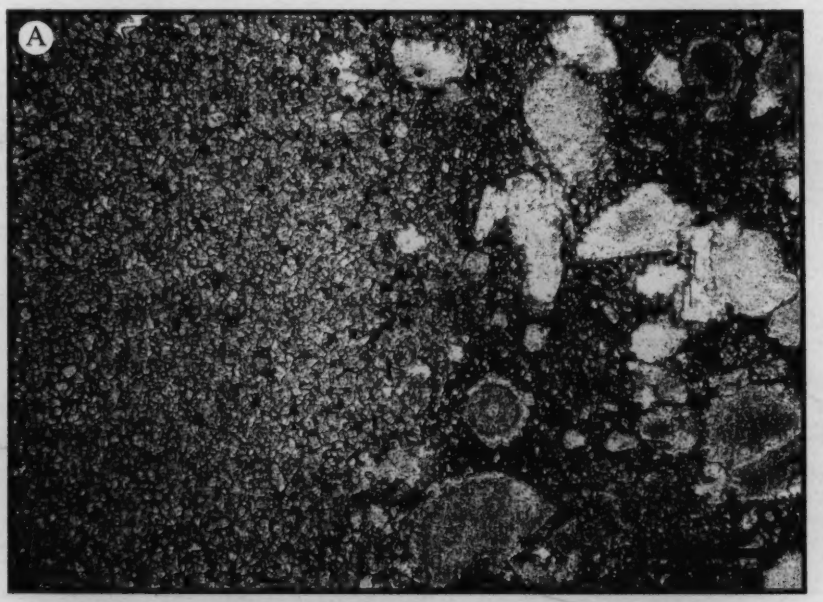


A. Fracture and moldic burrow porosity. Molds of halite hoppers (H) also hollow. 21/8-17-13-13W2/0, 2160.7 m.

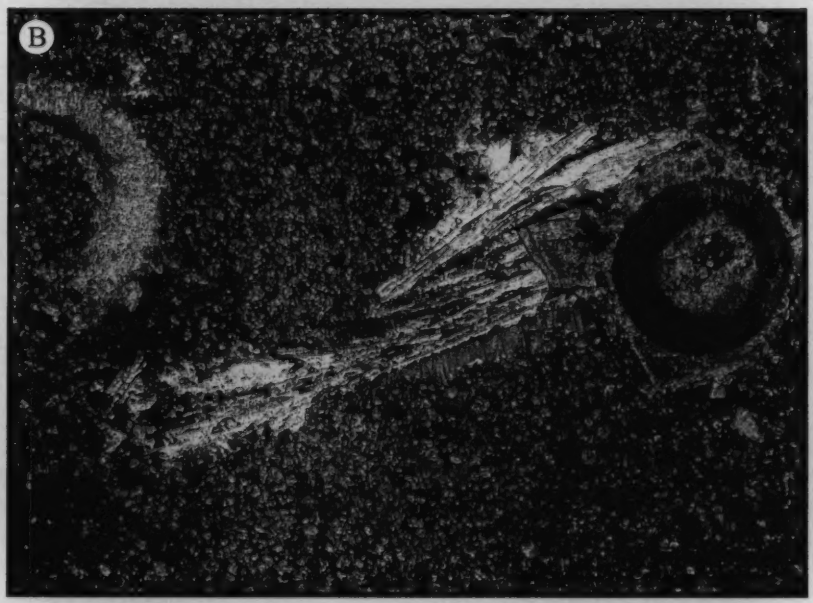


B. Fracture porosity. Polarized light. Scale bar 500 μm. 21/8-17-13-13W2/0, 2160.7 m.

Figure 5.16 Tyvan Pool Diagenesis: Facies 7

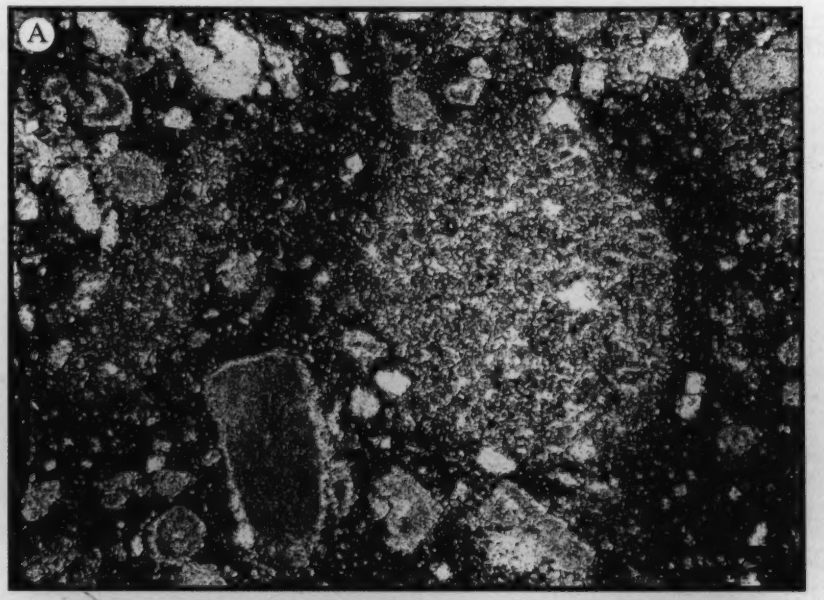


A. Dolomite mottle and intercrystalline porosity in matrix. Polarized light. Scale bar 1 mm. 21/8-17-13-13W2/0, 2154.9 m.

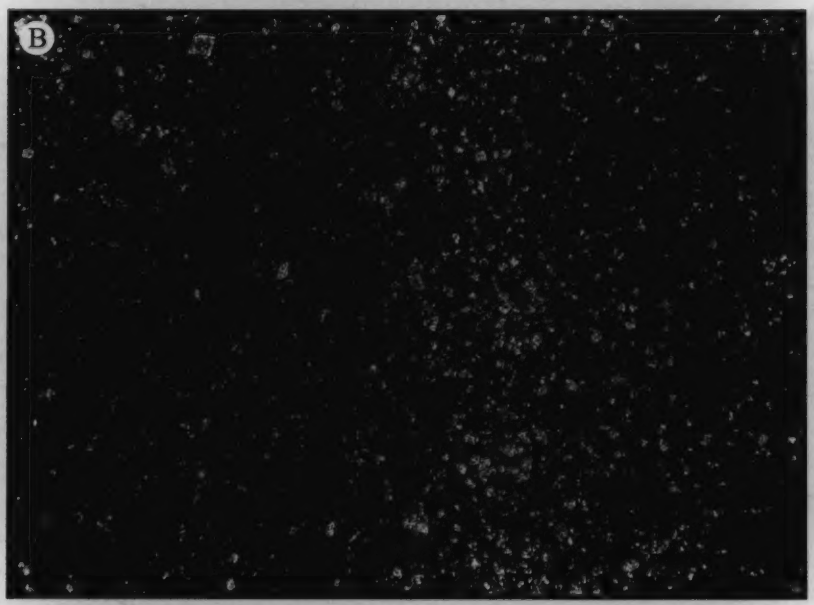


B. Cements: saddle dolomite and anhydrite. Polarized light. Scale bar 1 mm. 21/8-17-13-13W2/0, 2154.9 m.

Figure 5.17 Tyvan Pool Diagenesis: Facies 7 and 8

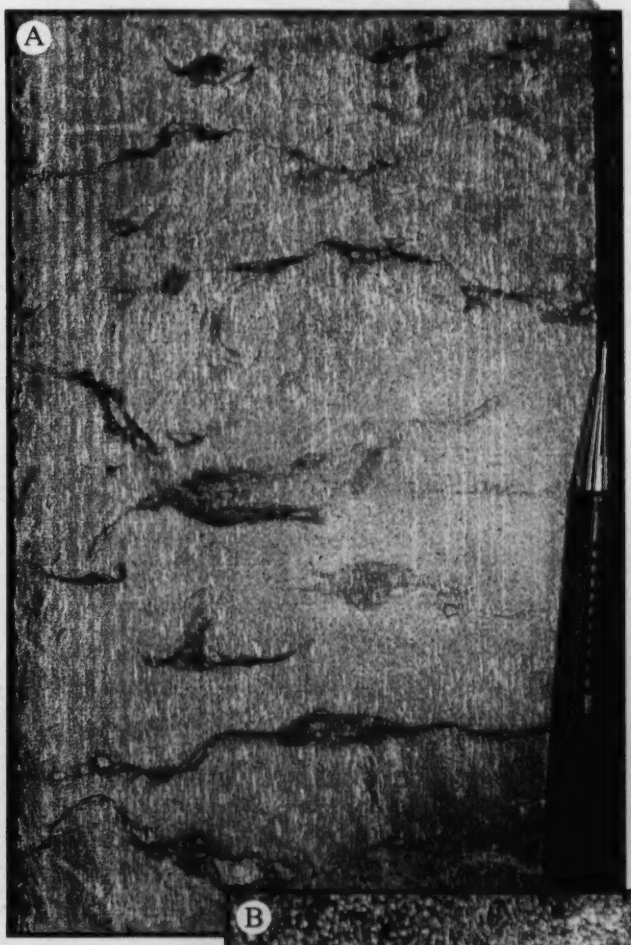


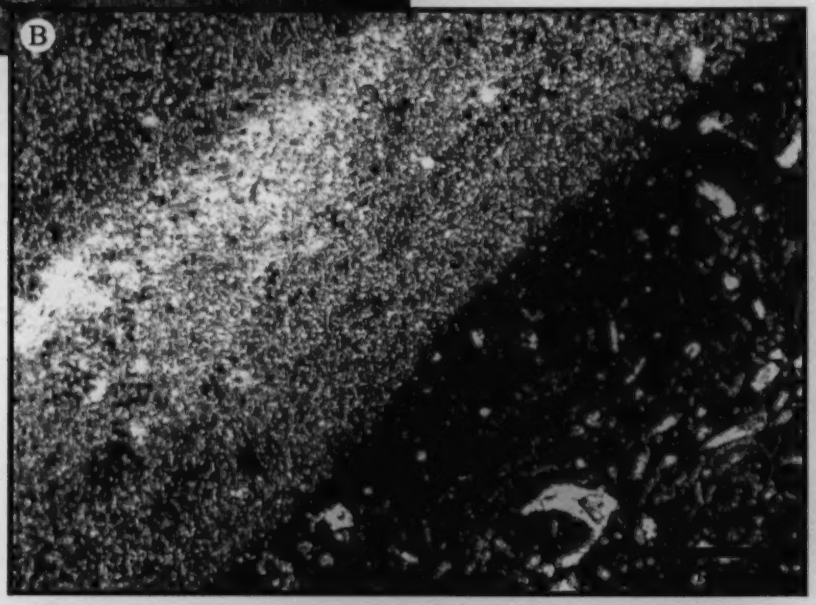
A. Calcareous matrix with allochems, in an undolomitized well. Polarized light. Scale bar 1 mm. 21/8-17-13-13W2/0, 2154.9 m.



B. *Planolites* and matrix. Burrow fill is more calcareous and contains fecal pellets. Polarized light. Scale bar 500 μm. 41/7-17-13-13W2/0, 2162.3 m.

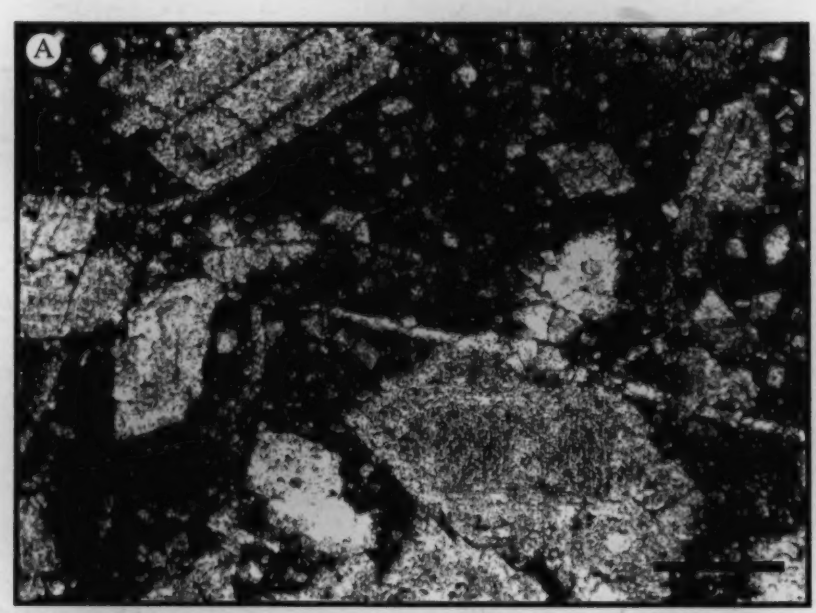
Figure 5.18 Tyvan Pool Diagenesis: Facies 9



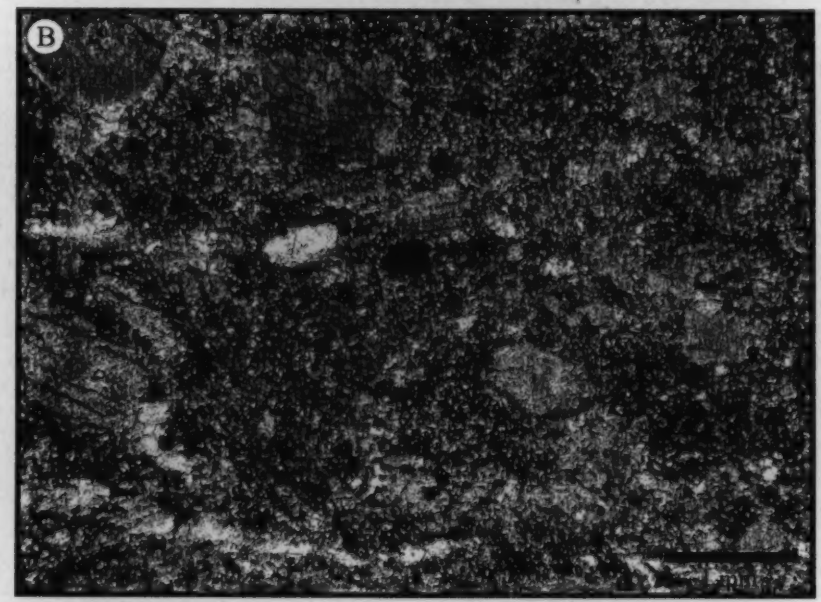


A. Pressure solution at burrow/mottle walls. 11/2-29-13-13W2/0, 2154.1 m.
B. Dolomitized burrow fill. Mottle wall with pressure solution. Polarized light. Scale bar 1 mm. 11/2-29-13-13W2/0, 2153.2 m.

Figure 5.19 Ceylon Pool Diagenesis: Facies 1



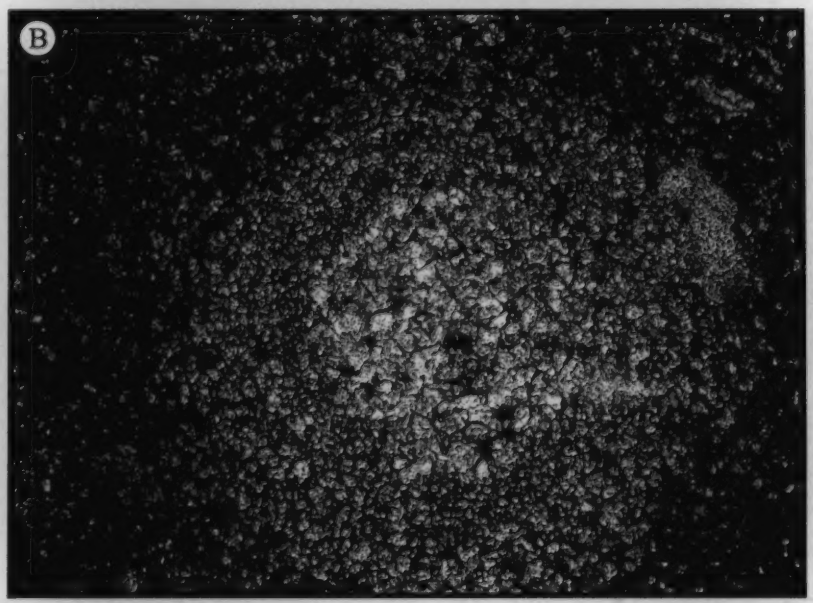
A. Calcareous matrix with allochems. Common syntaxial overgrowths on allochems. Polarized light. Scale bar 500 μm. 41/10-18-5-20W2/0, 2786.3 m.



B. Fully dolomitized interval. Note matrix dolomitization has not created valuable intercrystalline porosity as at Midale and Tyvan. Polarized light. Scale bar 500 μm. 11/5-8-6-19W2/0, 2734.2 m.

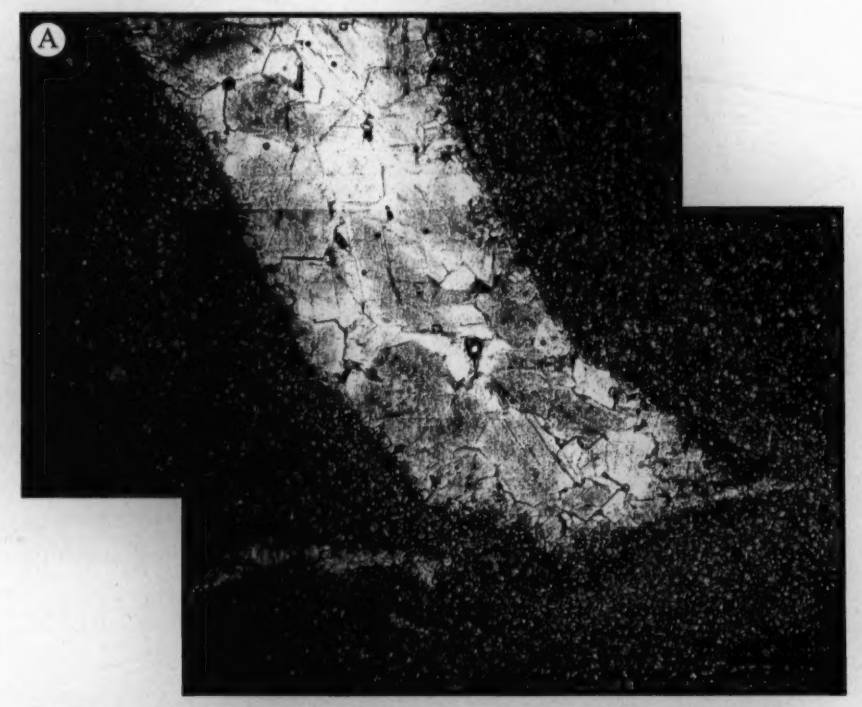
Figure 5.20 Ceylon Pool Diagenesis: Facies 2

A. Calcareous matrix with allochems and undolomitized *Planolites*. Polarized light. Scale bar 500 μm. 41/10-18-5-20W2/0, 2585.0 m.

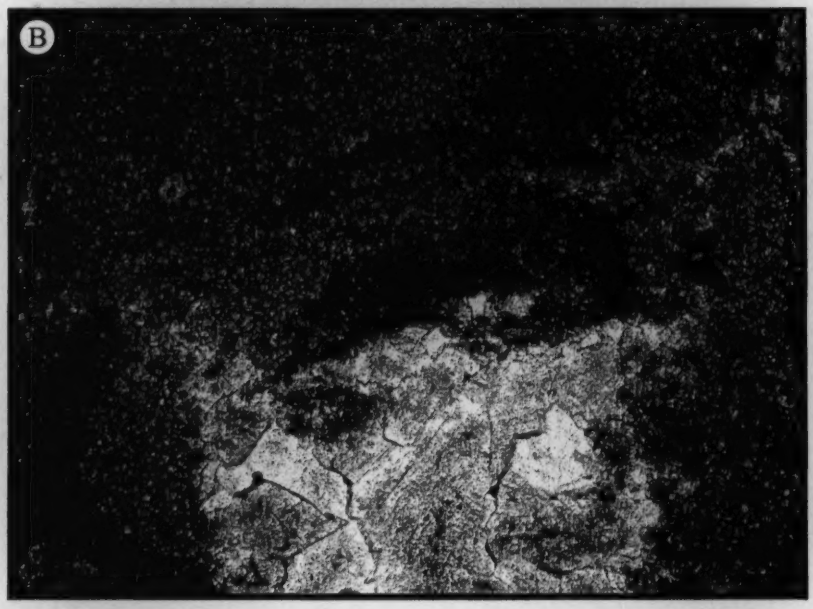


B. *Palaeophycus* with type 1 dolomite mottle. Polarized light. Scale bar 500 μm. 41/10-18-5-20W2/0, 2585.0 m.

Figure 5.21 Ceylon Pool Diagenesis: Facies 2

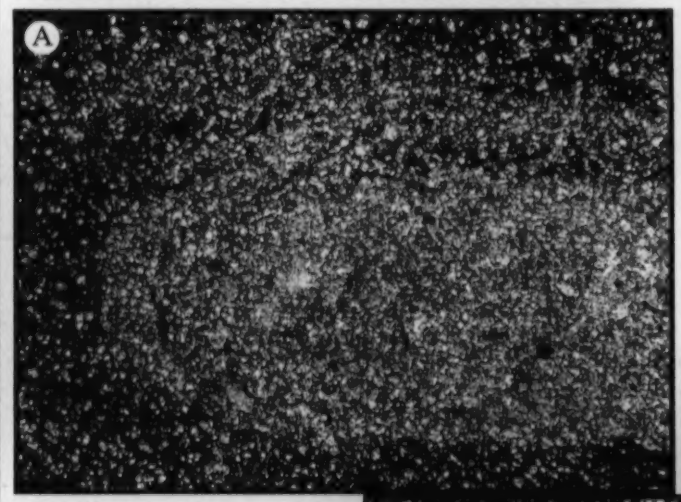


A. Core of *Palaeophycus* cemented by saddle dolomite. Polarized light. Scale bar 1 mm. 41/10-18-5-20W2/0, 2777.7 m.

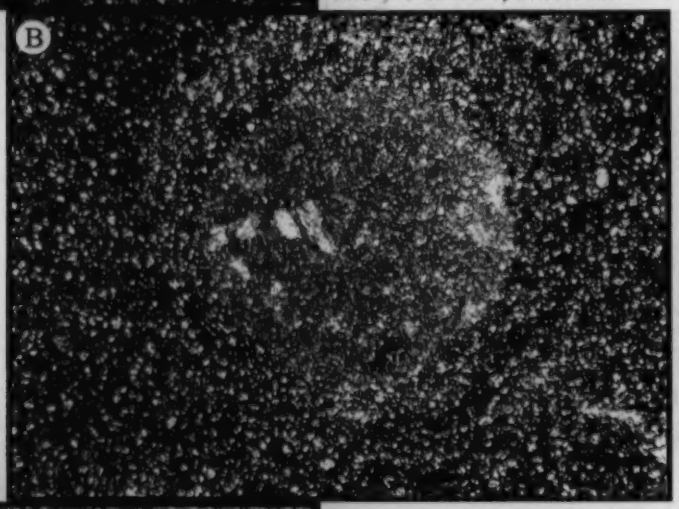


B. Mold after halite hopper in the burrow core cemented by saddle dolomite. Polarized light. Scale bar 1 mm. 41/10-18-5-20W2/0, 2780.6 m.

Figure 5.22 Ceylon Pool Diagenesis: Facies 4



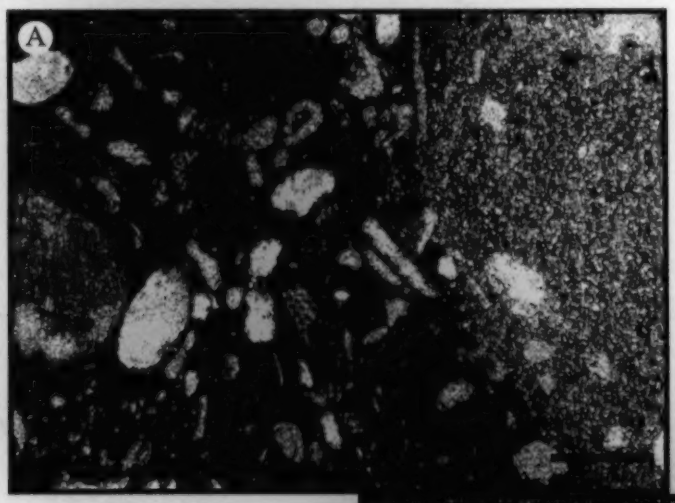
A. Limb of *Rhizocorallium*. Photo see Figure 4.11a. Polarized light. Scale bar 500 µm. 11/5-8-6-19W2/0, 2710.0 m.



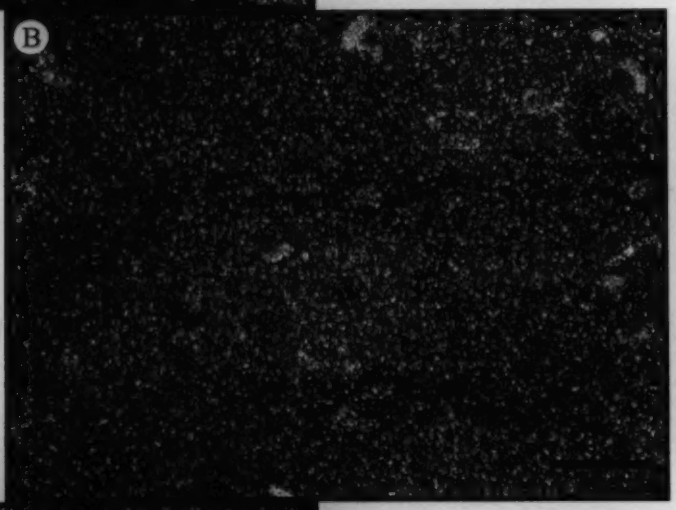
B. *Asterosoma* in a kukersite. Polarized light. Scale bar 500 µm. 11/5-8-6-19W2/0, 2710.0 m.

C. Stylolite in a kukersite. Polarized light. Scale bar 500 µm. 11/5-8-6-19W2/0, 2704.9 m.

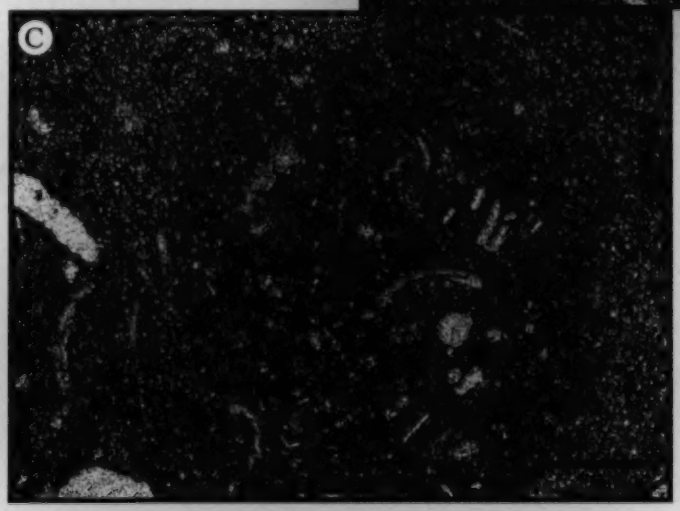
Figure 5.23 Ceylon Pool Diagenesis: Facies 6



A. *Planolites* and *Palaeophycus* lining (L) with type 1 dolomite mottle. Polarized light. Scale bar 1 mm. 11/5-8-6-19W2/0, 2710.0 m.

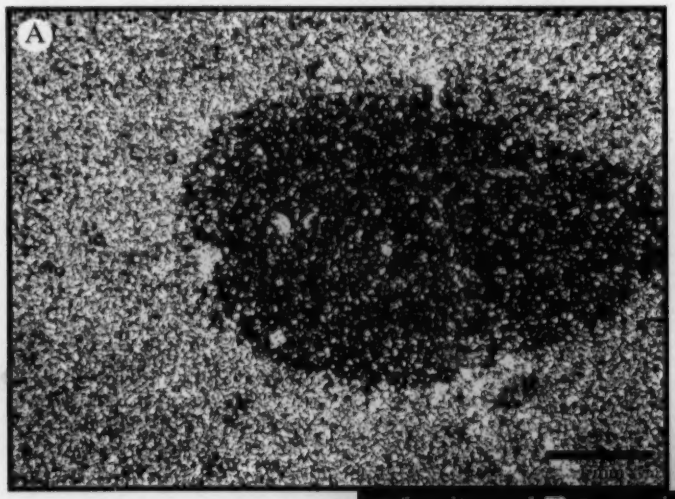


B. *Palaeophycus* with *G. prisca* in lining. Limited intercrystalline porosity. Polarized light. Scale bar 1 mm. 11/5-8-5-19W2/0, 2707.8 m.

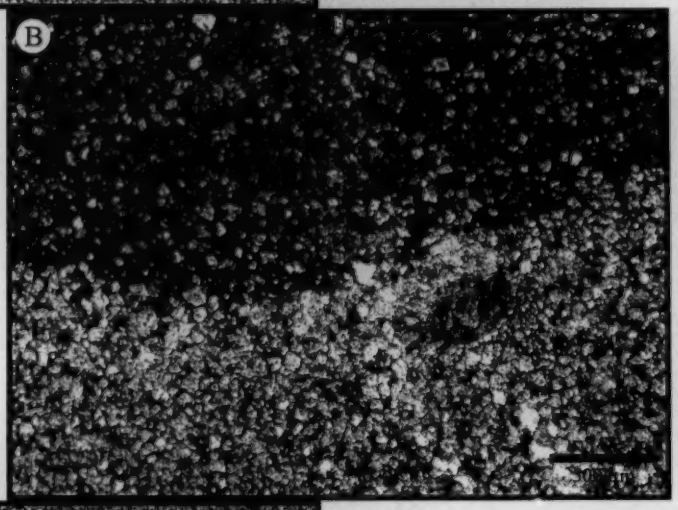


C. *Palaeophycus* with minor intercrystalline porosity in fill. Polarized light. Scale bar 1 mm. 11/5-8-5-19W2/0, 2707.8 m.

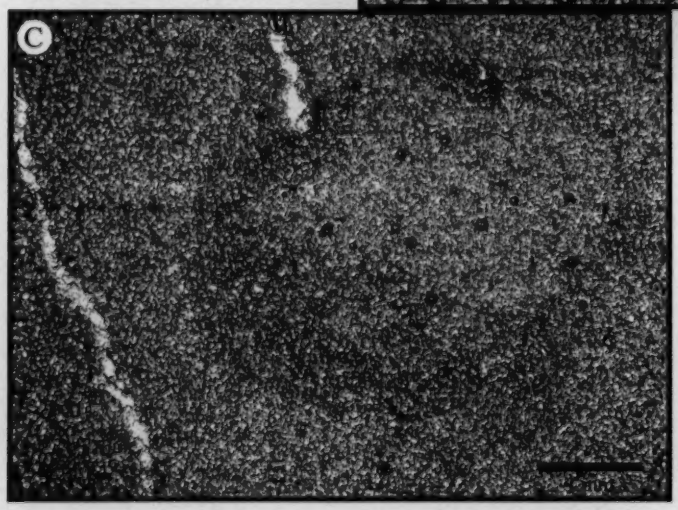
Figure 5.24 Ceylon Pool Diagenesis: Facies 8



A. *Planolites* fill is calcareous. Polarized light. Scale bar 1 mm. 41/10-18-5-20W2/0, 2773.9 m.

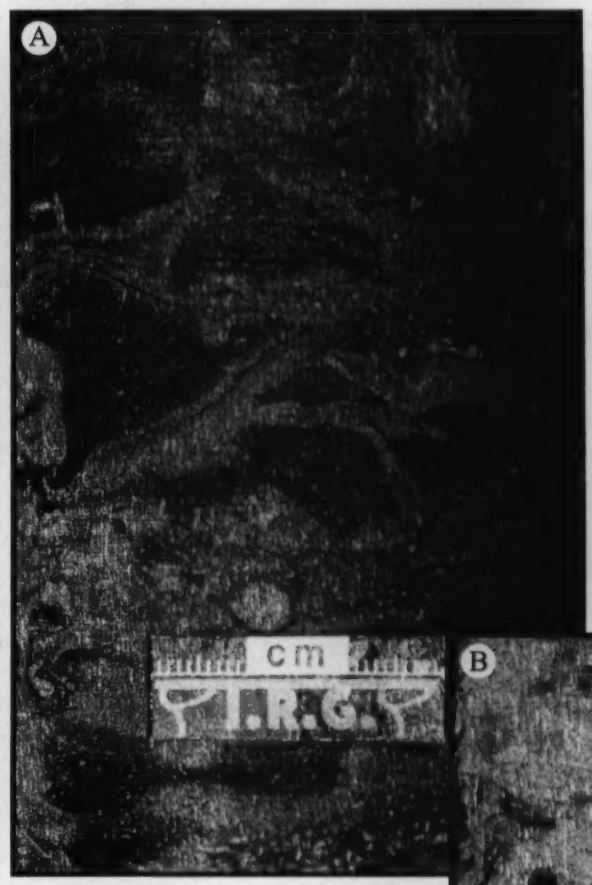


B. Wall of *Planolites* in image A. Polarized light. Scale bar 500 µm. 41/10-18-5-20W2/0, 2773.9 m.



C. Increased intercrystalline porosity in fill of *Planolites*. Fracture porosity cemented by coarse dolomite. Polarized light. Scale bar 1 mm. 41/10-18-5-19W2/0, 2762.4 m.

Figure 5.25 Diagenetic Fabrics



A. Fractures in dolomite mottles filled by matrix sediment. Evidence for earlier lithification of dolomite mottles. 21/11-35-6-11W2/0, 2596.2 m.

B. Dissolution has increased fracture porosity, by enlarginh fractures. 21/8-17-13-13W2/0, 2158.1 m.

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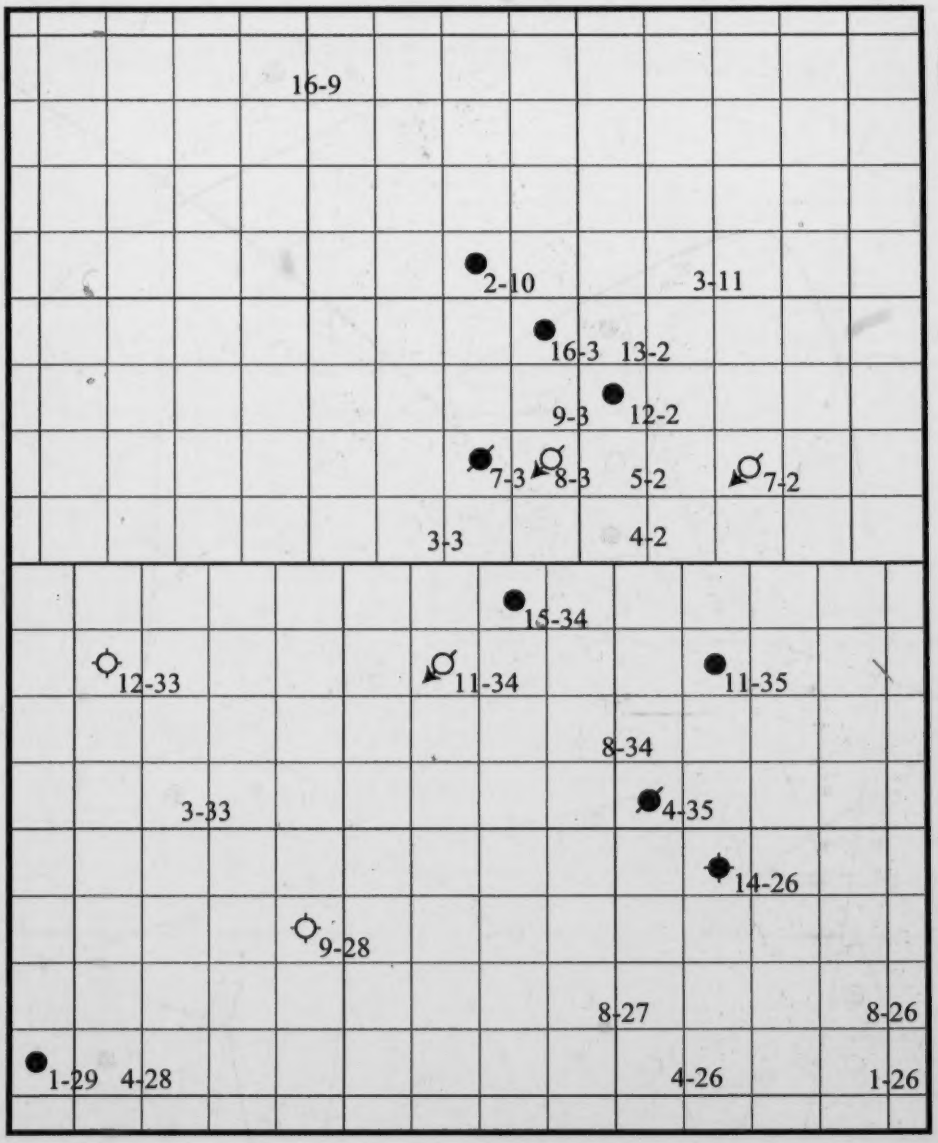
APPENDIX 1.

Figure A.1 Midale Area Wells



Legend

Yellow Wells with Yeoman Core

Red Wells without Yeoman Core

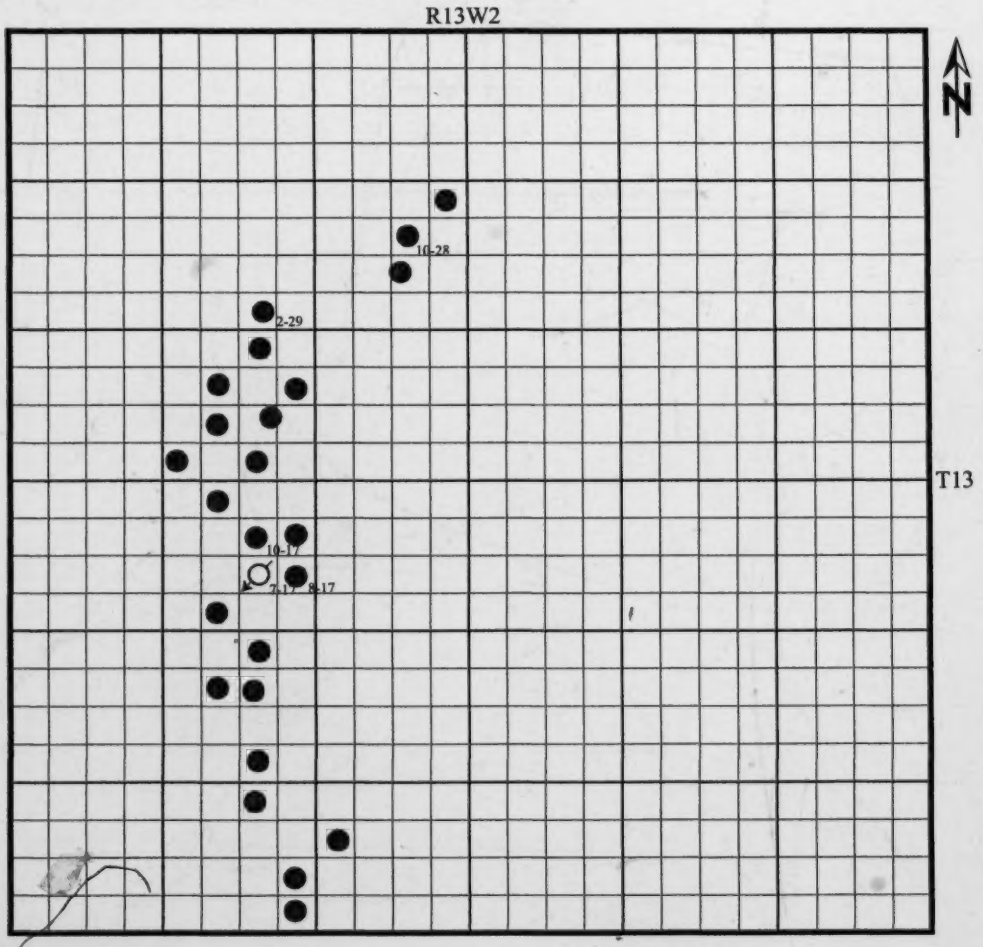
- Producing
- Injection Wells
- Abandoned
- Suspended
- Suspended

Wells Logged

11/9-28-6-11W2/0	12-2-7-11W2/0
31/11-34-6-11W2/A	11/7-3-7-11W2/0
41/4-35-6-11W2/0	01/8-3-7-11W2/0
11-35-6-11W2	21/16-3-7-11W2/0
7-2-7-11W2	2-10-7-11W2/0

Figure A.2

Tyvan Area Wells



Legend

Red Wells with Yeoman Core

Yellow Wells without Yeoman Core

- Producing
- Injection Wells
- Abandoned
- Suspended

Logged Wells

41/7-17-13-13W2

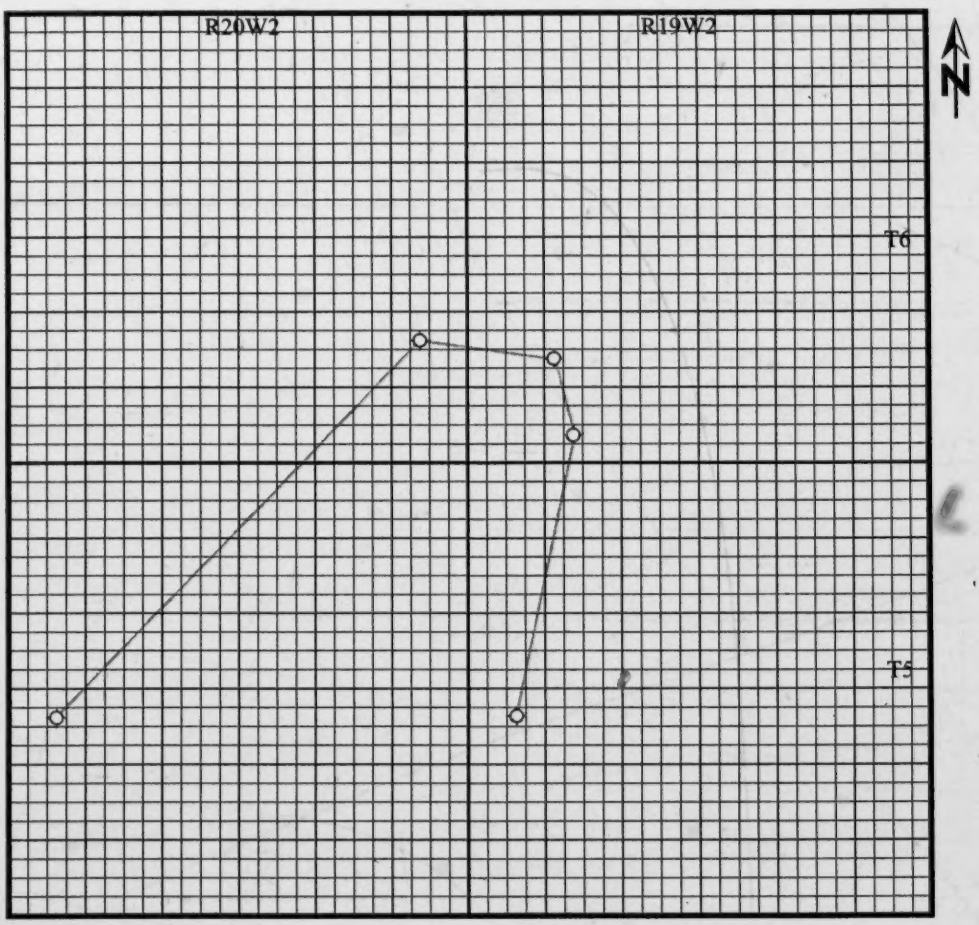
21/8-17-13-13W2

11/10-17-13-13W2

01/10-28-13-13W2

11/2-29-13-13W2

Figure A.3 Ceylon Area Wells



Legend	Wells Logged
Red Wells with Yeoman Core	01/10-18-5-19W2
Yellow Wells without Yeoman Core	41/10-18-5-20W2
● Producing	41/6-5-6-19W2
Injection Wells	11/5-8-6-19W2
Abandoned	42/11-12-6-20W2
Suspended	

APPENDIX 2.

SAMPLES CUT FOR DETAILED EXAMINATION

Location	Sample ID	Depth	Facies	TS	*G.*
41/4-35-6-11W2/0	4-35	?	2		
01/12-2-7-11W2/0	12-2A	2590.3 m	3		
01/12-2-7-11W2/0	12-2B	2590.3 m	2		
01/12-2-7-11W2/0	12-2-1	2596.3 m			
21/11-35-6-11W2/A	M-B7-C2	2595.59 m	2		
21/11-35-6-11W2/A	35-P5	2576.11 m	11		
21/11-35-6-11W2/A	35-P9	2581.75 m	9		
21/11-35-6-11W2/A	35-P11	2585.83 m	9		
21/11-35-6-11W2/A	35-P14	2589.22 m	7		
21/11-35-6-11W2/A	35-P16	2591.47 m	5		
21/11-35-6-11W2/A	35-P23/11-35-2	2597.25 m	2		*G.*
21/11-35-6-11W2/A	35-P24	2600.18 m	3		
21/11-35-6-11W2/A	11-35-1	2584.75 m	9		*G.*
11/7-3-7-11W2/0	7-3-1	2611.8 m	1		
11/7-3-7-11W2/0	7-3-14	2606.32 m	1		
11/7-3-7-11W2/0	7-3-3	2604.5 m	1/2 contact		
11/7-3-7-11W2/0	7-3-4	2604.2 m	2		
11/7-3-7-11W2/0	7-3-5	2603.0 m	2		
11/7-3-7-11W2/0	7-3-6	~2600.5 m	2		
11/7-3-7-11W2/0	7-3-7	2588.2-.36 m	4	X	
11/7-3-7-11W2/0	7-3-8	2584.0 m	6		
11/7-3-7-11W2/0	7-3-9	2582.4-.45 m	6		*G.*
11/7-3-7-11W2/0	7-3-10	2581.3 m	7		
11/7-3-7-11W2/0	7-3-11	2581.1-.2 m	7		
11/7-3-7-11W2/0	7-3-12	2276.8	9		
11/7-3-7-11W2/0	7-3-13	2577.0	9	X	*G.*
41/2-10-7-11W2/0	2-10-1	2594.17 m	2		
41/2-10-7-11W2/0	2-10-2	2594.0 m	2		
41/2-10-7-11W2/0	2-10-3	2592.91 m	2		
41/2-10-7-11W2/0	2-10-4	2589.95 m	3		
41/2-10-7-11W2/0	2-10-5	2589.52 m	2/3 contact		
41/2-10-7-11W2/0	2-10-6	2586.55 m	3/5 contact		
41/2-10-7-11W2/0	2-10-7	2181.18 m	4		*G.*
41/2-10-7-11W2/0	2-10-8	2579.41 m	4		
41/2-10-7-11W2/0	2-10-9A	2578.80 m	7		
41/2-10-7-11W2/0	2-10-9B	2578.80 m	7		
41/2-10-7-11W2/0	2-10-10	2574.82 m	9		
41/2-10-7-11W2/0	2-10-11	2574.32 m	9		
41/2-10-7-11W2/0	2-10-12	2571.94 m	9		
41/2-10-7-11W2/0	2-10-13	2571.2-.4 m	9		

X: No thin section cut.
G: Sample examined for organic matter assemblages.

Location	Sample ID	Depth	Facies	TS	*G.*
31/11-34-6-11W2/A	11-34-1	2596.07 m	5/6 contact		
31/11-34-6-11W2/A	11-34-2	2596.24 m	5		
31/11-34-6-11W2/A	11-34-3A	2600.65 m	6		
31/11-34-6-11W2/A	11-34-3B	2600.65 m	6		
31/11-34-6-11W2/A	11-34-4	2602.0 m	5		
31/11-34-6-11W2/A	11-34-5	2602.01 m	4		*G.*
31/11-34-6-11W2/A	11-34-6	2604.22 m			
31/11-34-6-11W2/A	11-34-7	2608 m	4		
31/11-34-6-11W2/A	11-34-8A	2606.07 m			
31/11-34-6-11W2/A	11-34-8B	2606.07 m	5		
31/11-34-6-11W2/A	11-34-9	2607.46-2607.63 m	5	X	
31/11-34-6-11W2/A	11-34-10	~2598.41 m	7		
42/11-12-6-20W2/0	SP1	2684.61 m	7/8 contact		
42/11-12-6-20W2/0	SP2	2685.0 m	10		
42/11-12-6-20W2/0	SP3	2685.5	10		
42/11-12-6-20W2/0	SP4	2686.25	10		
42/11-12-6-20W2/0	SP5	2686.8	10		
42/11-12-6-20W2/0	SP6	2687.2	10		
42/11-12-6-20W2/0	SP7	2687.87	10		
42/11-12-6-20W2/0	SP8	2690.75	?		
42/11-12-6-20W2/0	SP9	2691.85 m	?		
42/11-12-6-20W2/0	SP10	2693.66	?		
42/11-12-6-20W2/0	11-12-C1	?2683.6-2684.0	11	X	
42/11-12-6-20W2/0	11-12-C2	2684.61 m	10/11 cont	X	
42/11-12-6-20W2/0	11-12-C3	2688.2 m	10	X	
42/11-12-6-20W2/0	11-12-C4	2689.8-.9 m	?	X	
11/5-8-6-19W2/0	5-8-B1	2734.2 m	1-2 contact		
11/5-8-6-19W2/0	5-8-B2	2734.0-.3 m	1-2 contact		
11/5-8-6-19W2/0	5-8-B3	2737.40 m	1		
11/5-8-6-19W2/0	5-8-B4	2711.65 m	4		
11/5-8-6-19W2/0	5-8-B5	2711.02 m	6		*G.*
11/5-8-6-19W2/0	5-8-B6-1	2709.95 m	4		*G.*
11/5-8-6-19W2/0	5-8-B6-2	2709.95 m	6		*G.*
11/5-8-6-19W2/0	5-8-B7	2707.84 m	6		
11/5-8-6-19W2/0	5-8-B8-1	2706.6 m	10		
11/5-8-6-19W2/0	5-8-B8-2	2704.9 m	10		
11/5-8-6-19W2/0	5-8-B9	2705.57 m	10		
11/5-8-6-19W2/0	5-8-B10	2717.75 m			
41/6-5-6-19W2/0	6-5-52	2746.40 m	8		
41/6-5-6-19W2/0	6-5-S1	2731.60 m	6		
01/10-18-5-19W2/0	19-S1	~2760 m	10		
01/10-18-5-19W2/0	19-S2	2762.4 m	6?		
01/10-18-5-19W2/0	19-P7	~2762.9 m	6		
01/10-18-5-19W2/0	19-P15	2767.64 m	2		
01/10-18-5-19W2/0	19-P27	2772.28 m	2		

X: No thin section cut.
G: Sample examined for organic matter assemblages.

Location	Sample ID	Depth	Facies	TS	*G.*
41/10-18-5-20W2/0	20-CP3	2772.33 m	2 or 6		
41/10-18-5-20W2/0	20-C10	2773.91 m	8		
41/10-18-5-20W2/0	20-C6	2774.65 m	2		
41/10-18-5-20W2/0	20-C6A	2774.65 m	2		
41/10-18-5-20W2/0	20-C7	2774.85 m	8		
41/10-18-5-20W2/0	20-C7B	2774.85 m	8		
41/10-18-5-20W2/0	20-CP7	2775.13 m	8		
41/10-18-5-20W2/0	20-C8	2775.92 m	6		
41/10-18-5-20W2/0	20-C9	2776.79 m	2		
41/10-18-5-20W2/0	20-C11	2777.72 m	2		
41/10-18-5-20W2/0	20-C4	2779.21 m	2		
41/10-18-5-20W2/0	20-C5	2780.6 m	2		*G.*
41/10-18-5-20W2/0	20-CP21	2781.83 m	8		
41/10-18-5-20W2/0	20-C2	2781.83 m	8		
41/10-18-5-20W2/0	20-C3	2784.5 m	?		
41/10-18-5-20W2/0	20-CP24	2784.96 m	2		
41/10-18-5-20W2/0	20-C1	2786.32 m	1		
41/10-18-5-20W2/0	20-CP29	2787.15 m	1		
41/10-18-5-20W2/0	20-CP31	2788.1 m	1		
41/10-18-5-20W2/0	20-S1	2783.70 m	8		
41/7-17-13-13W2/0	7-17-T1	2168.4 m	?		
41/7-17-13-13W2/0	7-17-T2	2167.56 m	4		
41/7-17-13-13W2/0	7-17-T3	2163.5 m	7		
41/7-17-13-13W2/0	7-17-T4	2163.4 m	7		
41/7-17-13-13W2/0	7-17-T5	2162.3 m	8		
41/7-17-13-13W2/0	7-17-T6	2156.12 m	10		
41/7-17-13-13W2/0	7-17-T7	2154.4 m	10		
41/7-17-13-13W2/0	7-17-T8	2153.6 m	10		
41/7-17-13-13W2/0	7-17-T9	2152.35 m	11		
41/7-17-13-13W2/0	7-17-T10	2160.35 m	9	X	
21/8-17-13-13W2/0	8-17-T1	2143.5m	11		
21/8-17-13-13W2/0	8-17-T2	2144.0 m	10		
21/8-17-13-13W2/0	8-17-T3	2145.35 m	10		
21/8-17-13-13W2/0	8-17-T4	2147.3 m	10		
21/8-17-13-13W2/0	8-17-T5	2147.8 m	10		
21/8-17-13-13W2/0	8-17-A1	2147.9 m	10		
21/8-17-13-13W2/0	8-17-A2	2150.6 m	9		
21/8-17-13-13W2/0	8-17-A3	2160.65 m	2		
21/8-17-13-13W2/0	8-17-A4	2172.1 m	2		
21/8-17-13-13W2/0	8-17-3	2154.9 m	7		
21/8-17-13-13W2/0	8-17-2	2167.3 m	3		*G.*
21/8-17-13-13W2/0	8-17-1A	2170.9 m	2		
21/8-17-13-13W2/0	8-17-1B	2170.9 m	2		
11/10-17-13-13W2/0	10-17-T1	2163.82 m	7		
11/2-29-13-13W2/0	2-29-T1	2153.22 m	9		

X: No thin section cut.
G: Sample examined for organic matter assemblages.